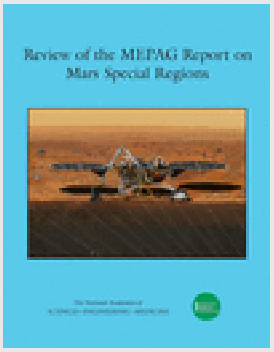

Review of the MEPAG Report on Mars Special Regions

DETAILS

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Space Studies Board
Division on Engineering and Physical Sciences

The National Academies of
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Cover: An artist's impression of NASA's Interior Exploration using Seismic Investigations, Geodesy and Heat Transport (InSight) lander on the surface of Mars. InSight is scheduled to be launched in March 2016 and it carries instruments built by NASA, the German Space Agency (DLR), and French Space Agency (CNES). The U.S.-built spacecraft bus is seen after deploying DLR's mole and heat flow probe (*left*) and CNES' seismometer (*right*). The type of geological analysis performed to certify that InSight will no access a Special Region is a model that can be used by future Mars missions. Image Credit: NASA/JPL-Caltech.

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The European Space Sciences Committee (ESSC) is the European Science Foundation's (ESF's) strategic board on space research. It aims to promote space science related activities, to facilitate the definition and the organization of space research programs in Europe, and to encourage the coordination of space research in concert with the European Space Agency, the European Commission and European Union, European scientific associations, national space agencies, and scientific organizations of other countries concerned with space-related research.

Following the establishment in 1974 under the auspices of the UK Royal Society of the "Provisional Space Science Board for Europe," the ESSC was established in 1975 as a Standing Committee of the newly created European Science Foundation. The ESSC had grown out of the need for a collaborative effort that would ensure European space scientists made their voices heard on the other side of the Atlantic, in an era when successive Apollo and space science missions had thrust the idea of space exploration into the collective conscious for the first time.

The ESSC remains just as relevant today as it acts as an interface with the European Space Agency (ESA), the European Commission, national space agencies, and ESF Member Organisations on space-related aspects.

The mission of the ESSC is to provide an independent European voice on European space research and policy. It is the ESF's Strategic Board on space research.

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Preface

The international consensus planetary protection policy, maintained by the Committee on Space Research (COSPAR) of the International Council for Science, requires specific constraints on the development and operation of spacecraft with the potential to enter so-called "Special Regions" on Mars. A Special Region is, roughly speaking, a location on or within Mars where Earth life might survive and proliferate. At NASA's request, the Mars Exploration Program Analysis Group (MEPAG) established the Special Regions Science Analysis Group (SR-SAG2) in October 2013 to re-examine the quantitative definition of a Special Region and proposed modifications to it, as necessary, based on the latest scientific results.

In October 2014, following the completion of the SR-SAG2 report—but prior to its formal publication in the November 2014 issue of the journal *Astrobiology*—John M. Grunsfeld, associate administrator of NASA's Science Mission Directorate, asked the Space Studies Board (SSB) of the National Academies of Sciences, Engineering, and Medicine "to review the conclusions and recommendations contained in the SR-SAG2 report and assess their consistency with current understanding of both the martian environment and the physical and chemical limits for the survival and propagation of microbial and other life on Earth." In addition, Dr. Grunsfeld (see Appendix D) noted that "it is our understanding that ESA [the European Space Agency] has requested the European Science Foundation (ESF) conduct a very similar review of the SR-SAG2 report. Given the close working relationship between NASA and ESA, in general, and their respective Planetary Protection Offices, in particular, the NRC should engage with ESF and explore the possibility of a joint study responsive to the needs of both agencies."

The SSB and ESF's European Space Sciences Committee have maintained a close working relationship for many decades and have published a number of joint reports, but none since 1998. Representatives from the two organizations worked closely with the planetary protection officers from NASA and ESA and developed the following statement of task for this joint activity:

> An ad hoc committee under the auspices of the National Research Council and the European Science Foundation will review the current planetary protection requirements for Mars Special Regions and their proposed revision as outlined in the 2014 Special Regions report of the Mars Exploration Program Analysis Group (MEPAG). The resulting report from the review shall include recommendations for an update of the planetary protection requirements for Mars Special Regions.

There were two reasons why both agencies took the seemingly unusual step of independently commissioning reviews of a review paper that was to be published in a peer-reviewed journal. First, there is the perception in some circles that MEPAG is not independent and that its views are too closely aligned with NASA's Mars Program Office.[1] Second, the planetary protection policies of both NASA and ESA, in accord with COSPAR policy, entail that planetary protection requirements imposed on spaceflight missions be determined following receipt of multidisciplinary scientific advice. ESF and the Academies provide unique interface with their respective scientific communities through their membership organisations and can provide independent advice taking into account all relevant areas of science, including the engineering and social sciences and the humanities. As a consequence, both NASA and ESA have established arrangements by which the Academies and ESF, respectively provide strategic advice on planetary protection.

It is important to note that neither the Academies nor ESF has an established mechanism for conducting a joint study with another organization. Thus, the joint committee, the Committee to Review the MEPAG Report on Mars Special Regions (hereafter the "review committee"), followed the standard administrative, organizational, appointment, and review procedures of both of its parent entities. In practice, the review committee followed all of the standard procedures relevant to a committee of the Academies plus a few extras mandated by ESF practice.

Staff from the Academies and ESF, together with the planetary protection officers from ESA and NASA, the lead author of SR-SAG2, and several of the prospective European members of the review committee met at the European Space Research and Technology Center (ESTEC) in Noordwijk, The Netherlands, on October 7, 2014, to hold preliminary discussions about the organization and schedule for the study. Following the ESTEC meeting, the final slate of both U.S. and European committee members was assembled, and formal appointment procedures by the Academies and ESF were completed by November 17. The U.S. participants in the joint activity were briefed and oriented during a conference call on December 2. The review committee held its first full meeting at the German Research Center for Geosciences in Potsdam, Germany, on December 16-17, 2014. The committee's second and final meeting was held at the Academies' Beckman Center in Irvine, California, on February 12-13, 2015. A full draft of the report was assembled during the Spring of 2015 and was sent to external reviewers on July 13.

The work of the review committee was made easier thanks to the important help, advice, and comments provided by numerous individuals from a variety of public and private organizations. These include the following, W. Bruce Banerdt (Jet Propulsion Laboratory), Catharine Conley (NASA), Gerhard Kminek (ESA), John Rummel (East Carolina University), and Colin Dundas (University of Arizona).

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the Report Review Committee of the National Academies of Sciences, Engineering, and Medicine. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their review of this report: Michael H. Carr (U.S. Geological Survey, retired), Charles Cockell (University of Edinburgh), François Forget (Univerisity of Paris 6), G. Scott Hubbard (Stanford University), Jonathan I. Lunine (Cornell University), John C. Priscu (Montana State University), Marcia J. Rieke (University of Arizona), and Pericles Stabekis (SETI Institute, retired).

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations nor did they see the final draft of the report before its release. The review of this report was overseen by François Raulin (University of Paris 12) and Louis J. Lanzerotti (New Jersey Institute of Technology), who were responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institutions.

[1] MEPAG is, according to its website, "a community-based forum designed to provide science input from the scientific community to NASA for the planning and prioritization of Mars future exploration activities, and to facilitate distribution of NASA Mars Program information to its members. Its Executive Committee is chartered by NASA's Lead Scientist for the Mars Exploration Program at NASA HQ . . . . NASA's Mars Program Office, located at [the Jet Propulsion Laboratory], has been directed to manage the logistics associated with the operations of MEPAG on behalf of NASA's Science Mission Directorate."

Contents

Executive Summary

Planetary protection is a guiding principle in the design of an interplanetary mission, aiming to prevent biological contamination of both the target celestial body and Earth. Planetary protection reflects both the frequently unknown nature of the space environment and the desire of the scientific community to preserve the pristine nature of planetary bodies until they can be studied in detail. The planetary protection policy maintained by the Committee on Space Research (COSPAR 2015) defines guidelines and specific requirements depending on the mission target and mission type based on the actual state of knowledge. New findings and new technology developments require the COSPAR planetary protection policy to be updated on a regular basis.

High-priority science goals, such as the search for life and the understanding of the martian organic environment, may be compromised if Earth microbes—that is, prokaryotic or eukaryotic single-cell organisms—carried by spacecraft grow and spread on Mars. This has led to the definition of "Special Regions" on Mars where strict planetary protection measures have to be applied before a spacecraft can enter these areas. The concept of a Special Region was developed as a way to refer to those places where the conditions might be conducive to microbial growth as we understand this process. In particular, this refers to places that might be warm and wet enough to support microbes that might be carried by spacecraft from Earth. COSPAR's planetary protection policy defines a Mars Special Region as a "region within which terrestrial organisms may be able to replicate, OR a region which is interpreted to have a high potential for the existence of extant martian life. Given current understanding, Special Regions are defined as areas or volumes within which sufficient water activity AND sufficiently warm temperatures to permit replication of terrestrial organisms may exist. In the absence of specific information, no Special Regions are currently defined on the basis of martian life."

The physical parameter space defined in COSPAR planetary protection policy (COSPAR 2015) for Special Regions is constrained by the following:

- Water activity: lower limit, 0.5; upper limit, 1.0;
- Temperature: lower limit, –25°C; no upper limit defined; and
- Timescale within which limits can be identified: 500 years.

In 2014, NASA requested the Mars Exploration Program Analysis Group (MEPAG) to review the definition of Special Regions. In particular, the MEPAG group SR-SAG2 (Special Regions Science Analysis Group 2) was asked to address a number of topics including the following:[1]

- "Reconsider information on the known physical limits of life on Earth . . ."
- "Evaluate new (i.e., since 2006) observational data sets and models from Mars that could be relevant to our understanding of the natural variations on Mars of water activity and temperature;" and
- "Reconsider the parameters used to define the term 'special region;' propose updates to the threshold values for temperature and water activity, as needed . . . "

The result of this analysis was published as a journal article (Rummel et al. 2014). In response to parallel requests from the European Space Agency (ESA) and NASA, the European Science Foundation and the U.S. National Academies of Sciences, Engineering, and Medicine initiated a joint review of the SR-SAG2 report by an international group of experts, the Committee to Review the MEPAG Report on Mars Special Regions (hereafter the "review committee").

The SR-SAG2 report provides findings about the Mars-relevant physical and chemical limits of life (as we know it), the various phenomena observed on Mars that might be indicative of a Special Region and possible mechanisms for their formation, and the considerations related to spacecraft-induced Special Regions. The findings are followed by a discussion of human spaceflight and, in particular, the resources needed to support humans on Mars. The report also discusses the findings and makes recommendations to COSPAR for consideration in updating the Special Regions definition in the COSPAR planetary protection policy.

The review committee discussed the SR-SAG2 report during two face-to-face meetings, via conference calls, and by email exchange. The committee notes that its statement of task (see the Preface) could be interpreted as requiring a review and update of the requirements levied on a spacecraft venturing into a Special Region. However, discussions with the planetary protection officers from NASA and ESA confirmed that the committee's task was limited to a review of the definition of a Mars Special Region and related revisions to COSPAR's planetary protection policy as proposed in the SR-SAG2 report. The review committee understands that its report, like the SR-SAG2 report, will inform the process by which COSPAR will revise and update its planetary protection policies.

The findings from the SR-SAG2 report were discussed by the committee in view of additional information from scientific publications not addressed by the SR-SAG2 report and from new knowledge obtained by ongoing space missions, field studies, and laboratory experiments. This included discussions about the breadth and depth of SR-SAG2 analysis with respect to survivability of life forms singularly versus in communities and SR-SAG2 approach to defining geographical areas as Special Regions. The review committee agreed with many of SR-SAG2's individual findings, including retaining the current limits for life specified by COSPAR, but arrived at different conclusions in some cases and is of the opinion that a more detailed consideration is necessary (see Chapters 2 to 5). The review committee summarizes its comments concerning the findings and presents a new definition of Special Regions that changes the way geographical features are designated as Special Regions in Chapter 6. In Chapter 7, the review committee revisits the scientific basis of the bioburden assays used to assess the microbiological contamination of spacecraft and comments on the necessity of updating planetary protection requirements so that they are based on the latest scientific facts concerning the probability of life surviving in the martian environment.

This report concludes with a series of appendices containing the following information: Suggestions for future research that could reduce uncertainties in the identification of Special Regions on Mars (Appendix A); a complete listing of the findings from the SR-SAG2 report and, where appropriate, the review committee's comments thereon (Appendix B); the letter from NASA requesting the Academies' participation in this study (Appendix D); and brief biographies of committee members and staff (Appendix E).

In summary, the review committee reached the following conclusions:

[1] See Rummel et al. (2014, Appendix A, pp. 945-946). Note that the identifiers "SR-SAG2 report" and "Rummel et al. 2014" are used interchangeably in this document.

1. The authors of the SR-SAG2 report are to be commended for their comprehensive review of the issues associated with Special Regions and the factors used to define them. The SR-SAG2 report contained 45 specific findings. Of these, the review committee does not support one (3-14), supports 13 in revised form (2-1, 2-4, 3-1, 4-1, 4-2, 4-8, 4-9, 4-14, 4-16, 5-3, 5-4, 5-7, and 5-9), suggests that two (4-6 and 4-7) be combined, proposes no changes for the remaining 29, and adds one new finding (6-1). The specific list can be found in Appendix B.

2. The environmental parameters used to define Special Regions (currently in the COSPAR policy and agreed upon in the SR-SAG2 report) of temperature and water activity are still appropriate. However, the review committee believes that if the detection of methane in the martian atmosphere—which may indicate biogenic activity—is confirmed, that may demand that the source region—that is, the location where methane is being produced—be designated as a Special Region.

3. The identification of Mars Special Regions is problematic for several reasons. First, detailed knowledge of the physical and chemical conditions of the surface and sub-surface of Mars at various scales is lacking, particularly the microscale. Second, current understanding of the ability of life to propagate is limited. It is not known if one, ten, or a million cells from a single species are required for propagation in an extraterrestrial environment. Alternatively, propagation may only be possible for microbial communities (i.e., collections of many different species). In view of the rapid development of powerful new techniques in biology and the increase in knowledge of the martian environment by ongoing and future space missions, the current practice of reassessing the concept of a Special Region and its definition every 2 years is both appropriate and essential.

4. The specific terrains identified as Special Regions in both the COSPAR policy and in the SR-SAG2 report (i.e., "gullies, and bright streaks associated with gullies, pasted-on terrains, subsurface below 5 meters, others, to be determined, including dark streaks, possible geothermal sites, fresh craters with hydrothermal activity, modern outflow channels, or sites of recent seismic activity" and "spacecraft-induced Special Regions") are best regarded as "Uncertain Regions." The final determination of a Special Region would depend on the review of the latest scientific knowledge about a specific site in order to verify if it is within the environmental parameters defining Special Regions, taking into consideration the potential existence of microscale habitats.

In addition, the review committee makes one recommendation.

> ***Recommendation:*** Maps should only be used to illustrate the general concept of Special Regions and should not be used to delineate their exact location. Uncertain Regions in planned landing ellipses should be evaluated on a case-by-case basis as part of the site selection process. The goal of such an evaluation is to determine whether or not the landing ellipse contains water, ice, or subsurface discontinuities with a potential to contain hydrated minerals that could be accessed via a landing malfunction or by the operation of subsurface-penetrating devices (e.g., drills). As an example, landing site analysis will likely include a geological analysis, drawing on the Mars geologic literature (covering a broad range of relevant topics, including ground truth at previous lander locations) as well as orbital imaging, infrared spectroscopy, gamma-ray spectroscopy, and ground-penetrating radar sounding of the specific region.

Finally, the review committee proposes the following update to the definition of a Special Region (COSPAR 2015): A Special Region is defined as a region within which terrestrial organisms are likely to replicate. Any region which is interpreted to have a high potential for the existence of extant martian life forms is also defined as a Special Region.

Given current understanding of terrestrial organisms, Special Regions are defined as areas or volumes within which sufficient water activity AND sufficiently warm temperatures to permit replication of Earth organisms may exist. The physical parameters delineating applicable water activity and temperature thresholds are given below:

- Water activity: lower limit, 0.5; upper limit, 1.0;
- Temperature: lower limit, −25°C; no upper limit defined; and
- Timescale within which limits can be identified: 500 years.

Observed features for which there is a significant (but still unknown) probability of association with liquid water, and which should be considered as Uncertain Regions and treated as Special Regions until proven otherwise:

- Sources of methane (if identified);
- Recurring slope lineae;
- Gullies and bright streaks associated with gullies;
- Pasted-on terrains;
- Caves, subsurface cavities and subsurface below 5 meters; and
- Others, to be determined, including dark slope streaks, possible geothermal sites, fresh craters with hydrothermal activity, modern outflow channels, or sites of recent seismic activity.

Spacecraft-induced special regions are to be evaluated, consistent with these limits and features, on a case-by-case basis.

Organizations proposing to investigate any region that may meet the criteria above, have the responsibility to demonstrate, based on the latest scientific evidence and mission approach, whether or not their proposed landing sites are or are not Special Regions.

In the absence of specific information, no Special Regions are currently identified on the basis of possible martian life forms. If and when information becomes available on this subject, Special Regions will be further defined on that basis.

1

Planetary Protection and Mars Special Regions

Planetary protection is the term given to the practice of protecting solar system bodies (i.e., planets, moons, comets, and asteroids) from contamination by Earth life (so-called forward contamination) and protecting Earth from possible life forms that may be returned from other solar system bodies (so-called back contamination). The 1967 United Nations Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Bodies states that all countries party to the treaty "shall pursue studies of outer space, including the Moon and other celestial bodies, and conduct exploration of them so as to avoid their harmful contamination." Internationally, technical aspects of planetary protection are developed through deliberations between space agencies and national and international scientific organizations, and the international consensus policy is maintained by the Committee on Space Research (COSPAR), an interdisciplinary committee of the International Council of Science, which consults with the United Nations in this area.

In COSPAR's Planetary Protection Policy (COSPAR 2015), planetary protection requirements for each mission are categorized according to the nature of the target body (e.g., a planet, moon, comet, or asteroid) and the type of encounter the spacecraft will have with it (e.g., flyby, orbiter, or lander). Specific outbound mission target and/or mission type combinations are organized into four planetary protection categories (Category I to IV), depending on the degree to which the target body is likely to provide clues about the origins of life and chemical evolution. Planetary bodies of little interest to such studies (e.g., Mercury) are assigned to Category I, and no specific planetary protection requirements are levied. However, a spacecraft landing on a target body of interest to the origins of life and chemical evolution that has a significant chance of contamination by Earth life (e.g., Mars) is assigned to Category IV and must undergo stringent cleaning and bioload-reduction processes. Missions returning extraterrestrial samples to Earth are assigned to Category V, a planetary protection classification reserved for inbound missions.

NASA and ESA maintain planetary protection policies and administer associated procedures to ensure compliance with them. The planetary protection officers of both agencies oversee compliance with formal implementation requirements that are assigned to each mission. Agency policies are informed by the most current scientific information available about the target bodies and about life on Earth.

Planetary protection policies are not static but evolve over time based on the increasing knowledge and understanding of both planetary environments and the physical and chemical limits of terrestrial life. Conclusions and recommendations generated by internal and external advisory groups chartered by space agencies such as NASA and ESA are weighted and assessed in an iterative manner by COSPAR's Panel on Planetary Protection (PPP). Consensus policy recommendations developed by the PPP are then forwarded for discussion and ultimate approval by COSPAR's Bureau and Council prior to becoming official COSPAR policy. The development of the concept of Special Regions on Mars is a good example of how planetary protection policies are developed and evolve as new information becomes available.

MARS SPECIAL REGIONS

Observations conducted by NASA's Mars Global Surveyor in the late-1990s and early-2000s led to the discovery of transient activity in martian gullies suggesting that liquid water may have flowed on the surface of Mars in recent times (see, for example, Malin and Edgett 2000). This discovery had an important impact on planetary protection, demonstrating that some regions may be more suitable to life than others (Meltzer 2011).

In April 2002, COSPAR and the International Astronomical Union convened a workshop in Williamsburg, Virginia, to discuss planetary protection policies (Rummel 2002). The workshop resulted in a revision of COSPAR's policies and, in particular, established a new mission category—Category IVc—for spacecraft accessing a Special Region on Mars (COSPAR 2003, pp. 67-74). COSPAR defined a Special Region as a zone "within which terrestrial organisms are likely to propagate, or a region which is interpreted to have a high potential for the existence of extant martian life forms. Given the current understanding, this is to apply to regions where liquid water is present or may occur. Specific examples include, but are not limited to: subsurface access in an area and to a depth where the presence of liquid water is probable, penetrations into the polar caps, [and] areas of hydrothermal activity." (COSPAR 2003, p. 71).

In 2005, NASA adopted COSPAR's concept of a Special Region within its planetary protection policy. In addition, NASA requested the National Research Council[1] (NRC) to conduct a study to assess the body of policies, requirements, and techniques designed to protect Mars from Earth-originating organisms that could interfere with and compromise scientific investigations (NRC 2006, p. 1). The resulting NRC report, *Preventing the Forward Contamination of Mars*, concluded that there was insufficient data to distinguish between Special Regions on Mars and regions that are not special (NRC 2006, pp. 4 and 61-63). The committee proposed a new classification system, which would replace COSPAR's Categories IVa through IVc, with Category IVn for Non-Special Regions and Category IVs for Special Regions (NRC 2006). In addition, the NRC committee commented: "Until measurements are made that permit distinguishing confidently between regions that are special on Mars and those that are not, NASA should treat all direct-contact missions (i.e., all category IV missions) as Category IVs missions" (NRC 2006, p. 118-119). In other words, the NRC recommended that all of Mars be considered a Special Region until additional observational data with better resolution can be obtained. If implemented, this recommendation required that all Mars landers be subjected to the most stringent—so-called Viking-level—bioload reduction procedures.

The programmatic consequences of subjecting all Mars landers to Viking-level bioload reduction led NASA to request that the Mars Exploration Program Analysis Group (MEPAG) charter a so-called Science Analysis Group (SAG) to look at Special Regions. In particular, the MEPAG group—SR-SAG—was asked "to develop a quantitative clarification of the definition of 'special region' that can be used to distinguish between regions that are 'special' and 'non-special'" and to undertake "a preliminary analysis of specific environments that should be considered 'special' and 'non-special'" (Beaty et al. 2006).

The SR-SAG found that COSPAR's definition of Special Regions needed additional clarification; specifically, the uses of the words *propagate* and *likely,* which can have different meanings and interpretations (Beaty et al. 2006, p. 684). The SR-SAG also constrained physical variables that could be used to define a Special Region, such as the following: how long they exist (about 100 years), the maximum depth of penetration by a spacecraft (about 5 m into the crust), and the lower limit for the survival of terrestrial life in terms of temperature (–15°C or –20°C including margin) and water activity (0.62 or 0.5 including margin) (Beaty et al. 2006, pp. 684-691). The SR-SAG report concluded by proposing a new definition of Special Region that retained the original COSPAR definition and added to it a set a clarifications and implementation guidelines (Beaty et al. 2006, p. 719).

[1] Effective July 1, 2015, the institution is called the National Academies of Sciences, Engineering, and Medicine. References in this report to the National Research Council (NRC) are used in a historical context to refer to activities before July 1.

In 2007, COSPAR held a Mars Special Regions Colloquium, with the goal of reviewing the conclusions and recommendations contained in both the 2006 NRC and MEPAG (Beaty et al. 2006) reports and devising a consolidated definition of Special Regions. The report of the COSPAR Colloquium (Kminek et al. 2010) disagrees with the NRC 2006 report by stating that there is sufficient data to distinguish between "special" and "non-special regions" and it differs from SR-SAG report by reducing the lower temperature limit for the survival of terrestrial life from –20° C to –25° C (Kminek et al. 2010). The colloquium report also recommended that the definition of a Special Region and the list of terrains classified as "special" be reviewed every 2 years (Kminek et al. 2010).

MEPAG empaneled a new science analysis group (SR-SAG2) in the latter part of 2014 to revisit the concept of Special Regions on Mars following the recommendation of the COSPAR colloquium to review the standards every 2 years. The SR-SAG2 used the following general approach (Rummel et al. 2014):

- Clarifying the terms in the existing COSPAR definition;
- Establishing temporal and spatial boundary conditions for the analysis;
- Reviewing the data sets on the limits of microbial life and the availability of water on Mars;
- Identifying applicable threshold conditions for propagation;
- Evaluating the distribution of the identified threshold conditions on Mars;
- Analyzing on a case-by-case basis those purported environments on Mars that could potentially meet or exceed the biological threshold conditions;
- Describing conceptually the possibility for spacecraft-induced conditions that could exceed the threshold levels for propagation; and
- Considering the impact of special regions on potential future human missions to Mars.

The resulting SR-SAG2 report provided a comprehensive distillation of the current understanding of the limits of terrestrial life and relevant martian conditions and presented an analytical approach for considering special regions using current and future improvements in knowledge. The SR-SAG2 report determined that the lower limit for temperature should be –18°C and water activity (a_w) above 0.60 (Rummel et al. 2014, pp. 894-898) and updated the list of features on Mars that should be classified as "special," "non-special," and "uncertain" regions.[2] In reference to human missions, the SR-SAG2 found that although these locations would be preferable for potential resources, human missions should not contaminate special regions, and precautions should be taken to avoid converting non-special regions to special regions (Rummel et al. 2014).

The review committee understands that its report and SR-SAG2 report will be formally presented to and discussed at an international workshop, organized by COSPAR's PPP, to be held in Bern, Switzerland, on September 22-24, 2015. The workshop and successor activities are part of the process COSPAR is using to revise and update its planetary protection policies. Recommendations from the PPP will ultimately be forwarded to COSPAR's Bureau and Council for action and potential incorporation in COSPAR planetary protection policy.

THE SCOPE AND ORGANIZATION OF THIS REPORT

The review committee notes that its statement of task (see the Preface) appeared to contain two separate items: to "review the current planetary protection requirements for Mars Special Regions" and to review "their proposed revision as outlined in" the SR-SAG2 report. The first of these items could be interpreted as reviewing the requirements levied on a spacecraft venturing into a Special Region. However, extensive discussions between the committee and the planetary protection officers from NASA and ESA confirmed that the task was to discuss the requirements defining a Mars Special Region and modifications to those requirements as proposed in the SR-SAG2 report.

[2] According to the SR-SAG2 report (p. 888), uncertain regions are defined as follows: "Uncertain Regions. If a martian environment can simultaneously demonstrate the temperature and water availability conditions identified in this study, propagation may be possible, and those regions would be identified as Special Regions. Nonetheless, because of the limited nature of the data available for regions only sensed remotely, it may not be possible to prove that such environments are capable of supporting microbial growth. Such areas are therefore treated in the same manner as Special Regions until they are shown to be otherwise."

Given this understanding of the task, the review committee's assessment of the SR-SAG2 report revealed that the major items needing additional consideration and deliberations fell into three broad categories.

- *The potential for terrestrial organisms to survive and proliferate when subjected to environmental conditions likely to be found on Mars*. Important aspects of this topic include the following: current understanding of the physical and chemical limits for the survival of life on Earth, life in extreme environments, properties of multispecies communities, advantages of cells living in biofilms over planktonic single cells, the detectability of small-scale microbial habitats, and the processes likely to transport terrestrial contamination from a spacecraft landing site into a Special Region. Discussion of these topics can be found in Chapter 2.
- *The relationship between martian geological, hydrological, and mineralogical features and Special Regions.* Important aspects of this topic include the following: biotic and abiotic sources of methane on Mars; gullies, polar slope streaks, recurring slope lineae, and related features; snow and ice deposits; subsurface environments, caves, and cavities; and the phenomenon of deliquescence. Discussion of these topics can be found in Chapter 3.
- *Issues not falling into the two previous categories*. Such topics include considerations relating to human spaceflight (Chapter 4), the utility or otherwise of maps to delineate Special Regions and the implicit buffer zones around them (Chapter 5), new considerations relating to the definition of Special Regions (Chapter 6), and aspects of planetary protection not discussed in the SR-SAG2 report (Chapter 7).

The main text of this report is complemented by appendixes containing the following: suggestions for future research (Appendix A), the findings from SR-SAG2 and the committee's suggested revisions and updates (Appendix B), a glossary of technical terms and acronyms (Appendix C), the letter from NASA requesting the Academies' participation in this study (Appendix D), and biographical information on the committee and staff (Appendix E).

2

The Assessment of the Potential of Terrestrial Lifeforms to Survive and Proliferate on Mars in the Next 500 Years

Two of the three factors appearing in COSPAR's definition of a Special Region relate to physical variables—that is, the lower limits of water activity and temperature, and the third factor is a timescale. While the bulk of this chapter is concerned with physical variables and the role they play in determining whether or not terrestrial life might proliferate on Mars, it is instructive to consider the timescale first.

The rationale for choosing a timescale is related to our ability, or rather our inability, to predict what the environmental conditions on Mars might be at an arbitrary date in the future. The primary drivers of climatic change on Mars are oscillations in the planet's orbital parameters such as obliquity and eccentricity. But numerical integrations of dynamical models of the solar system are dominated by non-linear effects at large times, and so predictability is lost. Model calculations quoted in the SR-SAG2 report reveal that changes in key orbital parameters are small over a period of 500 years. Thermal models of Mars referenced in the SR-SAG2 report reveal that the changing orbital parameters are not expected to change the mean martian surface temperature by more than 0.2 K over the next 500 years (Finding 1-1).

FACTORS INFLUENCING THE PHYSICAL AND CHEMICAL LIMITS OF LIFE

The Mars-relevant physical and chemical limits of life (as we know it) summarized and discussed in the SR-SAG2 report focus on the following:

- The presence of chemical compounds that can be used by microbes[1] as a source of carbon, energy, and nutrients;
- The lower temperature limit for cell division;
- The lower temperature limit for metabolic activities;
- The potential decrease of the lower temperature limit in the presence of chaotropic compounds;
- The lower limit of water activity for cell division versus metabolic activities;
- The effects of atmospheric composition and pressure;
- The effects of ultraviolet and ionizing radiation; and
- The combined effects of environmental stressors.

[1] The term "microbe" is used throughout this report as a generic term denoting any prokaryotic or eukaryotic single-cell organisms.

In addition, the potential occurrence of small-scale habitats—those not detectable with existing and planned space instruments, especially in the subsurface—were also addressed in the SR-SAG2 report. In general, the review committee agrees with most of the findings and the conclusions in the SR-SAG2 report. However, the review committee believes that some important aspects of Special Regions were not discussed by SR-SAG2. In particular, the issues of translocation of terrestrial contamination and the behavior of multispecies populations in extreme environments, produce uncertainty in the determination of Special Regions, because such regions might not be isolated from the rest of the planet (translocation), because microbial communities could occupy dispersed, small-scale habitats or might be able to alter (e.g., through the synthesis of extrapolymeric substances and syntrophic consortial interactions) local environmental parameters and syntrophic consortial interactions. These issues, together with the present lack of knowledge about the limits of life on Earth and the uncertainty of the relationship between the large-scale and micro-scale environments at any given place make the definition of Special Regions difficult. The sections below expand on these topics and propose research topics that will help make the definition of Special Regions more effective.

INVESTIGATIONS OF THE LIMITS OF LIFE ON EARTH

The availability of powerful new techniques for the investigation of cellular and molecular processes has resulted in an enormous increase in knowledge about Earth's biodiversity and, in particular, the ability of only certain organisms to live in extreme environments. However, despite these advances, researchers still have a limited understanding of how microorganisms survive and replicate under extreme conditions. Laboratory studies allow the reproducible exposure of cultivable organisms to standardized, controlled conditions. However, in the past, most such studies were performed with single species, very often with type strains from culture collections and not with isolates obtained directly from extreme environments. Type strains sometimes lose their natural stress resistance because of their repeated cultivation under optimal conditions in the laboratory. In particular, microorganisms living in cold environments—such as psychrophiles and psychrotolerants—are not well understood. One reason for this is that the generally long replication time of this group of organisms requires long-term laboratory investigations extending over several years.

Contrary to laboratory studies with single species, field studies focus on in situ investigation of natural communities. Observations from extreme habitats on Earth provide insight into some of the survival and adaptation mechanisms of communities of organisms at specific periods of time (e.g., diurnal, seasonal, annual) and at different spatial scales. Quite often these investigations cannot be repeated because of the dynamic nature of indigenous microbial communities, their environmental setting, and the interactions that occur between microbes and the environments in which they live. The derivation of generalizations from such studies is challenging. Therefore, the review committee recognizes the need for scientific investigations that deepen our knowledge about the limits of life with a focus on survivability, adaptation, and evolution under martian conditions. The most important conditions are the temperature limits and the bioavailability of water, in particular, the potential utilization of atmospheric water vapor as sole source for water has not been proven, even if some observations suggest it (Azúa-Bustos et al. 2015; Jacobsen et al. 2015). Another important consideration concerns the ability of so-called chaotropic compounds to lower the temperature limit for cell division. As a result, the committee proposes to add text to SR-SAG2's Finding 3-1 (shown in italics):

SR-SAG2 Finding 3-1: Cell division by Earth microbes has not been reported below –18°C (255K).

Revised Finding 3-1: Cell division by Earth microbes has not been reported below –18°C (255K). *The very low rate of metabolic reactions at low temperature result in doubling times ranging from several months to year(s). Current experiments have not been conducted on sufficiently long timescales to study extremely slow-growing microorganisms.*

Suggestions for future research directions relating to the issues discussed in this section can be found in Appendix A.

LIFE IN EXTREME ENVIRONMENTS AND IN MULTISPECIES COMMUNITIES

The SR-SAG2 report identified the ability of microorganisms to withstand multiple stressors as an important area of research. Extreme ecosystems on Earth are often subjected to a multitude of conditions considered to push the limits of microbial life. For instance, surfaces of ice shelves in both the Arctic and Antarctic harbor conditions that combine multiple physiological stresses imposed on microorganisms, such as low temperatures, high levels of ultraviolet radiation, and several-fold annual variations in salinity (Mueller et al. 2005). Permafrost environments are subjected to long-term exposure to sub-zero temperatures, background radiation, limited liquid water availability, and frequent very-low-nutrient conditions.

In nature, microorganisms typically live and proliferate as members of communities rather than as single cells or populations. A widespread growth form of life in natural habitats occurs as multispecies biofilms where the cells are embedded in a self-produced extracellular matrix consisting of polysaccharides and proteins, which includes other macromolecules such as lipids and DNA. These so-called extrapolymeric substances (EPS) provide protection against different environmental stressors (e.g., desiccation, radiation, harmful chemical agents, and predators). Biofilms are highly organized structures that enable microbial communication via signaling molecules, disperse cells and EPS, distribute nutrients and release metabolites, and facilitate horizontal gene transfer.

The majority of known microbial communities on Earth are able to produce EPS, and the protection provided by this matrix enlarges their physical and chemical limits for metabolic processes and replication. EPS also enhances their tolerance to simultaneously occurring multiple stressors and enables the occupation of otherwise uninhabitable ecological niches in the microscale and macroscale. The presence of EPS within a microbial community has implications for several aspects of the SR-SAG2 report, including the physical and chemical limits for life, the dimension of habitable niches versus the actual resolution capability of today's instruments in Mars orbit, colonization of brines, and tolerance to multiple stressors. In extreme cold and salty habitats (e.g., brines of sea ice and cryopegs in permafrost), EPS has been found to be an excellent cryoprotectant (Goordial et al. 2013). For instance, production of EPS by the marine psychrophilic bacterium *Colwellia psychrerythraea* increases in response to low temperatures, to high pressure, and to salinity (Marx et al. 2009). Another example is the EPS produced by hypolithic microbial communities that develop on the undersides of translucent rocks in the Dry Valleys of Antarctica, which is thought to facilitate the water-holding capacity of cells and promote microbial survival, growth, and succession (Makhalanyane et al. 2013; de los Ríos et al. 2014).

The production of EPS enhances the resistance of cells to a wide variety of environmental stresses, when compared to their resistance in planktonic growth mode, and enables microbial communities to thrive in nearly any undisturbed environment that receives sufficient water and nutrients. Given the wide distribution and advantages that communities of organisms have when they live as biofilms enmeshed in copious amounts of EPS, it is likely that any microbial stowaways that could survive the trip to Mars would need to develop biofilms to be able to establish themselves in clement microenvironments in Special Regions so that they could grow and replicate. This consideration raises a fundamental question about the probability of a successful colonization by microbial contaminants from Earth in martian habitats, one recently formulated in an essay by Siefert et al. (2012). Studies have been conducted to determine the bioburden found on spacecraft and their assembly facilities (e.g., Satomi et al. 2006; Rettberg et al. 2006; Moissl-Eichinger et al. 2012, 2015). But, to date, there have been no experimental attempts to determine whether the number and type of cells that remain on spacecraft after sterilization and/or after launch and travel through space (e.g., even in low Earth orbit) are sufficient to establish a population and/or community of microorganisms within a Mars Special Region.

Suggestions for future research directions relating to the issues discussed in this section can be found in Appendix A.

DETECTABILITY OF POTENTIAL SMALL-SCALE MICROBIAL HABITATS

The definition of Mars Special Regions is based on temperature and humidity conditions that are measured on spatial scales that do not reflect these conditions within microscale niches that can be potential habitats for microbial communities. Physical and chemical conditions in microenvironments can be substantially different from those of larger scales. Although the SR-SAG2 report considered the microenvironment (Finding 3-10), the implications of the lack of knowledge about microscale conditions was only briefly considered.

There are many examples of small-scale and microscale environments on Earth (see e.g., Lindsay and Brasier 2006) that can host microbial communities, including biofilms, which may only be a few cell layers thick. The biofilm mode of growth, as noted previously, can provide affordable conditions for microbial propagation despite adverse and extreme conditions in the surroundings. On Earth, the heterogeneity of microbial colonization in extreme environments has become more obvious in recent years (e.g., Azúa-Bustos et al. 2015). To identify Special Regions across the full range of spatial scales relevant to microorganisms, a better understanding of the temperature and water activity of potential microenvironments on Mars is necessary. For instance, the interior of the crater Lyot in the northern mid-latitude has been described as an optimal microenvironment with pressure and temperature conditions that could lead to the formation of liquid water solutions during periods of high obliquity (Dickson and Head 2009). Craters, and even microenvironments underneath and on the underside of rocks, could potentially provide favorable conditions for the establishment of life on Mars, potentially leading to the recognition of Special Regions where landscape-scale temperature and humidity conditions would not enable it.

The review committee agrees with Finding 3-10 of the SR-SAG2 report but stresses the significance of the microenvironment and the role it might play on the definition of a Special Region in areas that (macroscopically speaking) would not be considered as such. This issue will be expanded on in Chapter 5.

Suggestions for future research directions relating to the issues discussed in this section can be found in Appendix A.

TRANSLOCATION OF TERRESTRIAL CONTAMINATION

Microbial cells and spores are fairly ubiquitous in Earth's atmosphere (Burrows et al. 2009; Després et al. 2012) and have been found in a diverse variety of other environments, including the deep ocean (Nunoura et al. 2015); in 3.6-km-deep groundwater accessed via South African gold mines (Moser et al. 2003); in sub-sea floor sediments (Schrenk et al. 2010); at almost 4 km depth in ice sheets above subglacial Lake Vostok (Priscu et al. 1999); in the outer reaches of the stratosphere (Pearce et al. 2009), and 70 km above Earth's surface (Imshenetsky et al. 1978). Atmospheric transport can move microbial cells and spores over long distances, as is known from investigations of foreign microbes delivered to North America from Africa via Saharan dust (Chuvochina et al. 2011; Barberàn et al. 2014) and Asia (Smith et al. 2012).

A potential problem with designating Special Regions on Mars is that viable microorganisms that survive the trip to Mars could be transported into a distant Special Region by atmospheric processes, landslides, avalanches (although this risk is considered minimal), meteorite impact ejecta, and lander impact ejecta. In addition to dilution effects, the flux of ultraviolet radiation within the martian atmosphere would be deleterious to most airborne microbes and spores. However, dust could attenuate this radiation and enhance microbial viability. In addition, for microbes growing not as single cells but as tetrades or larger cell chains, clusters, or aggregates, the inner cells are protected against ultraviolet radiation. Examples are methanogenic archaea like *Methanosarcina*, halophilic archaea like *Halococcus*, or cyanobacteria like *Gloeocapsa*. This is certainly something that could be studied and confirmed or rejected in terrestrial Mars simulation chambers where such transport processes for microbes (e.g., by dust storms) are investigated. The SR-SAG2 report does not adequately discuss the transport of material in the martian atmosphere. The issue is especially worthy of consideration because if survival is possible during atmospheric transport, the designation of Special Regions becomes more difficult, or even irrelevant. Experiments conducted in facilities such as the Mars Surface Wind Tunnel at NASA's Ames Research Center or the low-pressure recirculating wind tunnels in the Mars Simulation Laboratory at Aarhus University[2] may shed light on this issue.

Suggestions for future research directions relating to the issues discussed in this section can be found in Appendix A.

In summary, the SR-SAG2 report's assessment of the potential for terrestrial life to survive and proliferate on Mars is comprehensive. Of the 14 findings related to this topic (2-2, 2-3, and 3-1 through 3-12), the review committee finds no objection to 13 of them (see Appendix B) and proposes that a small caveat be added to Finding 3-1.

[2] For details of the Ames and Aarhus facilities see, respectively http://www.nasa.gov/centers/ames/business/planetary_aeolian_facilities.html and http://marslab.au.dk/windtunnel-facilities/wind-tunnel/.

3

Martian Geological and Mineralogical Features Potentially Related to Special Regions

The SR-SAG2 report described various phenomena observed on Mars that might be indicative of Special Regions and discussed possible mechanisms for their formation. Examples include recurring slope lineae (RSL) (Figure 3.1), slope streaks (Figure 3.2), polar dark dune streaks, gullies (Figure 3.3), craters, and caves. The detection of deliquescent minerals and the presence of water in the form of subsurface ice, snow, and liquid brines were considered in view of ambient martian temperature and pressure conditions and the potential bioavailability of water. In general, the review committee agrees with the relevant findings and conclusions in the SR-SAG2 report relating to these topics. However, in some cases the committee has different opinions. For example, the possible detection of methane in the martian atmosphere was seen by the review committee as an important new factor suggesting that methane source regions be designated as an Uncertain Regions. The sections below expand on these topics. Modified text in the findings is shown in italic font.

METHANE: POTENTIAL ABIOTIC AND BIOTIC SOURCES

The SR-SAG2 report concludes in Finding 2-4 that the detection of indigenous organic compounds on Mars at very low concentrations (e.g., Freissinet et al. 2015) should not be used to distinguish Special Regions. However, it is appropriate that special consideration be given to methane, recently detected near the surface of Mars (Webster et al. 2015).[1] The review committee asserts that the lack of knowledge about the source(s) and sink(s) that control the possible episodic release of methane requires that it be considered a special class of organic compound and that its source region(s), once identified, be designated as an Uncertain Region. The abiotic processes most likely to produce methane in the subsurface to account for its intermittency include serpentinization and hydrothermal processes. The dissociation of methane clathrates and the production of biogenic methane by contaminants of polyextremophile terrestrial methanogens delivered to Mars on spacecraft or by potentially existing martian methanogens could also release methane (Figure 3.4).

If unambiguously confirmed, methane is the first indigenous organic compound discovered on Mars. The presence of possible intermittent plumes of methane at various latitudes, in different geographical settings and different seasons, has made it difficult to attribute the source of methane to a single process or release mechanism

[1] The presence or absence of methane in the martian atmosphere remains highly controversial. For a contrary view see, for example, Zahnle et al. (2011) and Zahnle (2015).

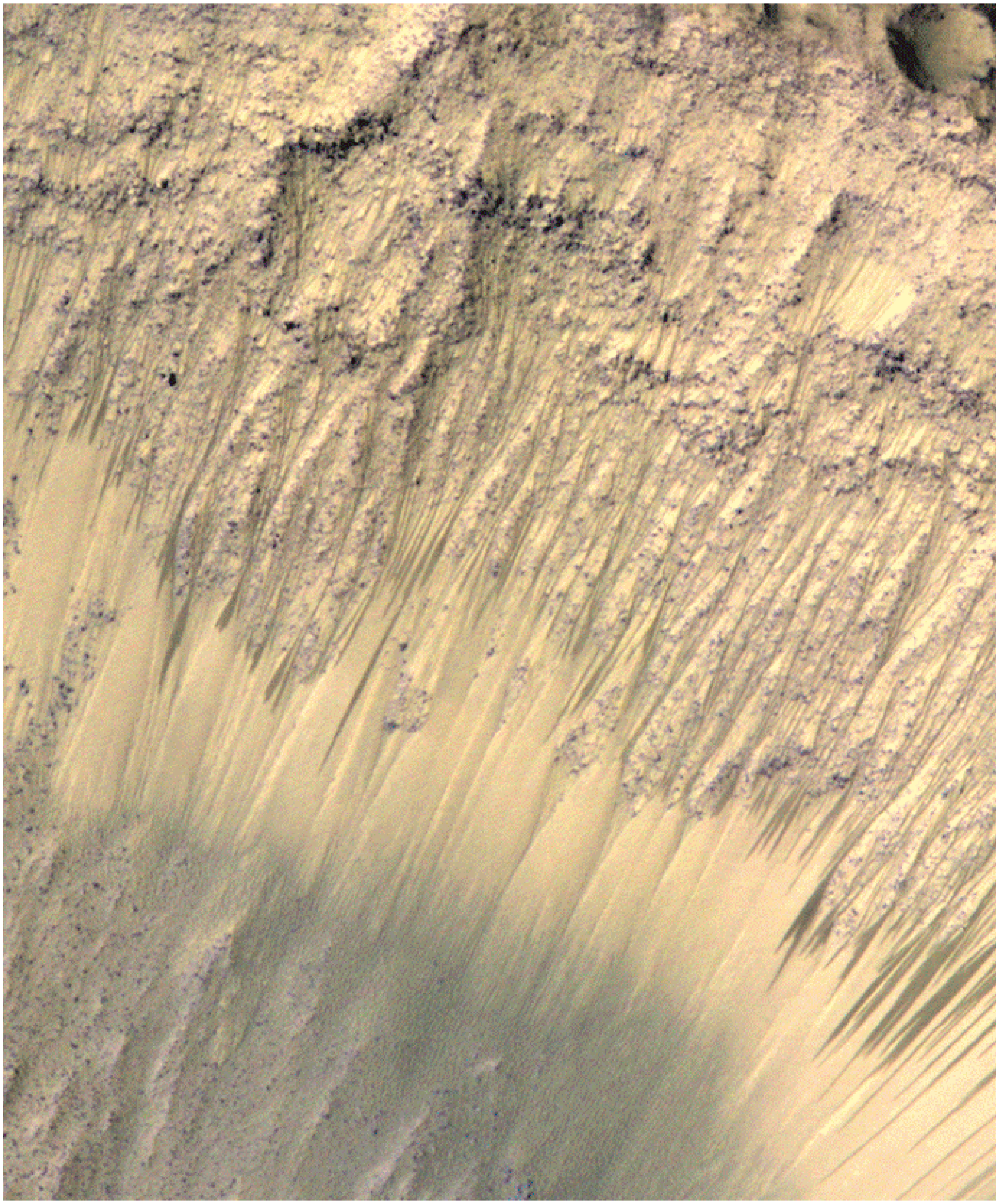

FIGURE 3.1 Recurring slope lineae (RSL) in a crater on the floor of central Valles Marinaris. RSL are narrow, dark markings on steep, rocky slopes in the equatorial and southern mid-latitude regions of Mars. They appear to incrementally lengthen during warm seasons and fade in cold seasons, which is best explained as a result of seasonal water seepage by terrestrial analogy, although the origin of water is unknown. This image shows an area approximately 200 m wide. SOURCE: Portion of HiRISE image ESP_031059_1685; courtesy of NASA/JPL/University of Arizona.

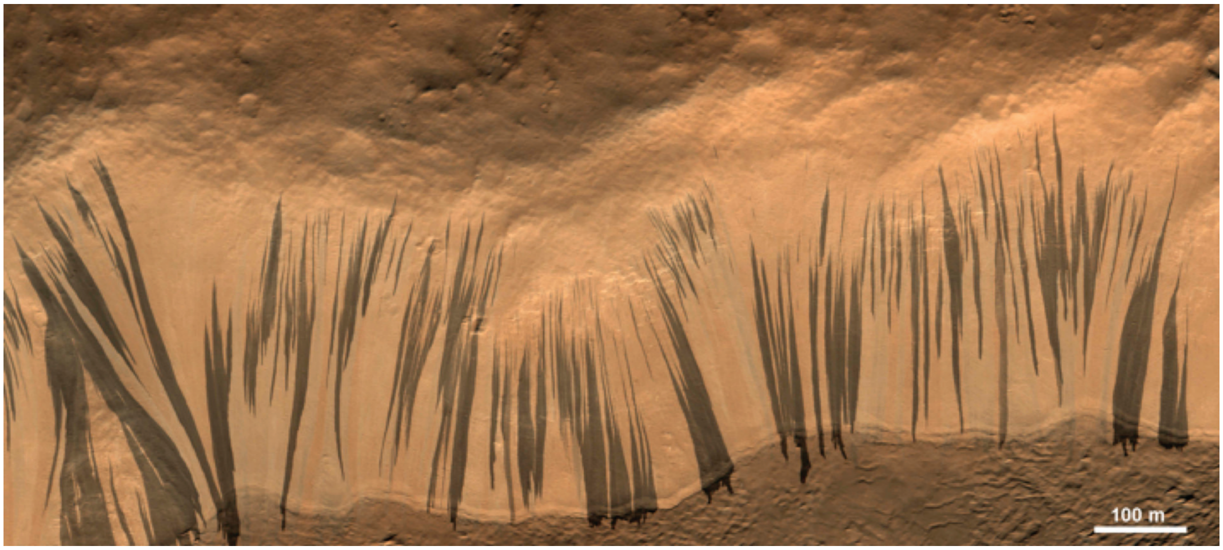

FIGURE 3.2 Many dark- and light-toned slope streaks on a dust-covered slope in the Acheron Fossae region of Mars (37.32°N, 229.11°E). Although the mechanism of slope streak formation and triggering is debated, slope streaks are commonly believed to be dark subsurface material exposed by the downward movement of very dry sand or fine-grained dust in a fluid-like manner, analogous to a terrestrial snow avalanche. The darkest slope streaks are the youngest, appearing to cross-cut and overlay older, lighter streaks, which are believed to be dark streaks that are lightening with the deposition of new dust on their surface. SOURCE: HiRISE image PSP_001656_2175 image; courtesy of NASA/JPL/University of Arizona.

(Komatsu et al. 2011). The time-transient nature of atmospheric methane in trace concentrations lasting from months to years (e.g., Webster et al. 2015) is consistent with the presence of active sources and multiple sinks for methane on Mars (Atreya et al. 2006). Locating the source(s) of methane and identifying the process(es) by which it is produced and/or released must remain key mission priorities because of the high potential that such processes operate at temperatures and water activity values that define Special Regions.

The likely processes that could individually, or together, produce or release enough methane from the subsurface to account for the atmospheric concentration observed on Mars include serpentinization, hydrothermal alteration, and the dissociation of methane clathrates (Sleep et al. 2004; Oze and Sharma 2005; Fonti and Marzo 2010; Osinski et al. 2013; Kargel 2004; Wray and Ehlmann 2011; Herri and Chassefière 2012). All three of these processes would likely involve and/or release liquid water (i.e., would imply a Special Region), albeit within the subsurface of Mars.

Given the relatively short lifetime inferred for the methane possibly detected on Mars, which is inconsistent with its anticipated photochemical lifetime (300-600 years; Wong et al. 2003; Lefèvre and Forget 2009), it is also important to consider the likelihood that multiple types of methane sinks might exist on Mars. Potential sinks of methane include oxidants produced in global dust storms and local dust devils (Delory et al. 2006) as well as highly reactive mineral surfaces produced by wind-driven erosion (Jensen et al. 2014).

The possibility cannot be excluded that Mars' subsurface could host indigenous anaerobic microbial communities dominated by lithoautotrophs that could be similar to methanogenic Archaea isolated from Siberian permafrost (Wagner et al. 2013). The general question of the habitability of Mars to lithoautotrophs has been examined by numerical modelling (Jepsen et al. 2007) and empirically by microbial growth experiments with autolithotrophs under simulated martian conditions. A putative food web on Mars was formulated on the basis of the metabolic capabilities iron-sulfur bacteria and on the minerals present on Mars (Bauermeister et al. 2014). Even if such putative microorganisms are not active today, they could become activated in spacecraft-induced Special Regions and survive present-day martian conditions. For example, Siberian permafrost methanogens have survived for 3 weeks

FIGURE 3.3 Mid-latitude martian gullies at 37.46°S, 222.95°E, exhibiting erosional alcoves, channels, and depositional aprons; all geological features that appear to be actively evolving and resemble landforms that on Earth are formed by water. Observations of gullies over the last decade reveal occasional mass wasting and show that they are currently active. However, present-day activity occurs when it is too cold for liquid water and is likely driven by dry granular processes involving CO_2 frost. This image shows an area approximately 1.5 km from top to bottom. SOURCE: HiRISE image ESP_033290_1420; courtesy of NASA/JPL/University of Arizona.

under simulated martian thermophysical conditions (Morozova et al. 2007). Such organisms are tolerant to multiple stresses (i.e., low temperatures, high salinity, and prolonged starvation), can grow on different martian regolith analogs when supplied with carbon dioxide and molecular hydrogen (Schirmack et al. 2015), and can tolerate periodic desiccation such that they can endure a_w shifts between 0.1 and 0.9 (Morozova and Wagner, 2007). Some permafrost isolates also show an extreme resistance to the effects of ultraviolet radiation (F_{37} = 14-15 kJ m^{-2}) and ionizing radiation (D_{37} = 6-7 kGy; Wagner, unpublished data) comparable to the most radiation-resistant bacteria *Deinococcus radiodurans* (Ito et al. 1983). Such microorganisms could live in potentially habitable environments on Mars, such as in subsurface caves (see the section "Caves and Subsurface Cavities" below); beneath or in the lower boundary layer of subsurface clathrates and the cryosphere; and in cryopegs, the lenses of ground that contain over-cooled (–9°C to –11°C) water brines that could periodically source so-called recurring slope lineae (see the next section of this chapter).

Section 3.1 of the SR-SAG2 report discussed the possibility that martian methane could be indicative of a biosphere on Mars. But, SR-SAG2 did not address what the review committee considers to be a central issue related to methane's occurrence in trace concentrations in the atmosphere.

If the methane on Mars is of biological origin, the planet either has an active biosphere that includes methanogens or the methane produced by an extinct biosphere could have been sequestered in methane clathrates in the

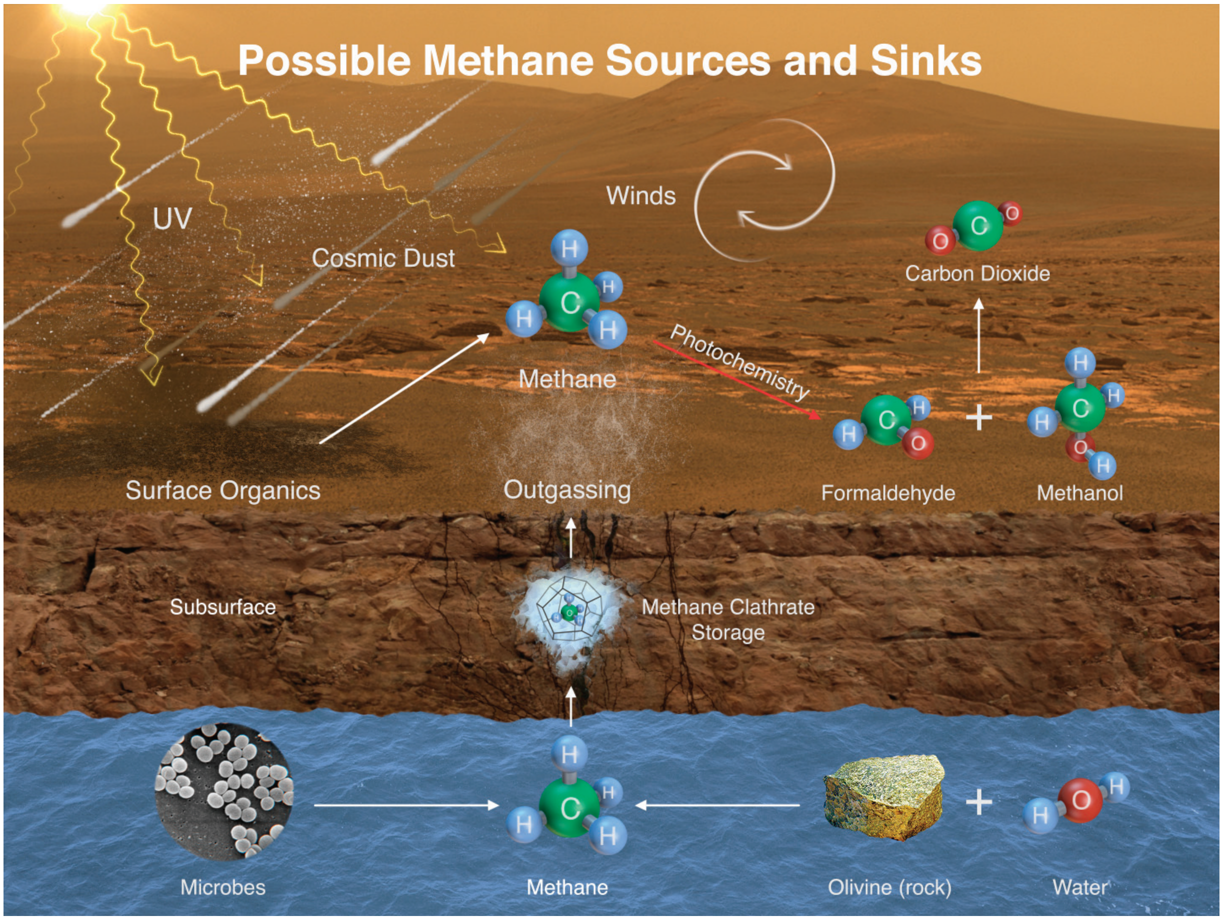

FIGURE 3.4 A schematic illustration of the known ways that methane (CH_4) could be added to or removed from the atmosphere, processes known, respectively, as methane sources and sinks. NASA's Curiosity Mars rover is searching for methane traces as a potential sign of life (a biomarker), as well as to gain an understanding of modern surface and subsurface organic processes on Mars. Curiosity has indeed detected fluctuations in methane concentration in the atmosphere, implying that both methane sources and sinks are currently at work in the martian environment. Detecting methane does not necessarily mean the presence of life. Methane can be generated by microbes as well as by non-biological processes, such as geochemical reactions, sunlight-induced reactions (photochemistry), or delayed release from subsurface methane stores. Reactions between water and olivine (or pyroxene) can generate methane. Ultraviolet (UV) radiation can induce photochemical reactions that produce methane from other organic compounds that are themselves formed by biological or non-biological means, such as comet dust falling on Mars. Recent or ancient subsurface methane may be stored within lattice-structured methane hydrates called clathrates and released over time, a source of modern atmospheric methane that may have formed in the past. Concentrations of atmospheric methane can drop due to redistribution or photochemical sinks. Wind on Mars can quickly reduce localized methane concentrations from an individual source. Just as methane can be generated through photochemistry, it can be broken down in the same way; sunlight-induced reactions oxidizing the methane through intermediary chemicals like formaldehyde and methanol into carbon dioxide, the predominant component of the martian atmosphere. SOURCE: NASA Jet Propulsion Laboratory/California Institute of Technology, "Possible Methane Sources and Sinks," image PIA19088, December 16, 2014, http://www.jpl.nasa.gov/spaceimages/details.php?id=pia19088; courtesy of NASA/JPL-Caltech/SAM-GSFC/University of Michigan.

Mars subsurface (Atreya et al. 2007, Chassefière 2009, Mousis et al. 2013). In either case, methane gas could be released today either because methane-producing organisms are still alive in the subsurface (this would imply a Special Region that hosts extant Mars life), or changes in the physical conditions have resulted in the dissociation of methane clathrates and the release of the gas to the surface where it has been measured. In the latter case, if episodic clathrate dissociation in the subsurface environment was accompanied by the production of liquid water at those locations, the region would be a Special Region.

Even if the methane production is abiotic, liquid water will likely be involved and, thus, the location where the methane is generated is best considered as an Uncertain Region, to be treated as a Special Region until proven otherwise. Moreover, abiotic methane could, potentially, be used as a source of carbon and energy by putative martian methanotrophs. It is imperative that further research be conducted to discriminate the origin of methane on Mars. Therefore, the review committee proposes a revision of the Finding 2-4.

> **SR-SAG2 Finding 2-4:** Organic compounds are present on Mars (or in the martian subsurface); although in very low concentrations in samples studied to date. *Such detections are not used to distinguish Special Regions on Mars.*

> **Revised Finding 2-4:** Organic compounds are present on Mars (or in the martian subsurface); although in very low concentrations in samples studied to date. *Abiotic or potentially biotic processes can explain the detection of episodic plumes of methane at various latitudes. In both cases, liquid water solutions would be involved. Therefore, the source regions of methane are considered as Uncertain Regions, even if the methane production is abiotic.*

Suggestions for future research directions relating to the issues discussed in this section can be found in Appendix A.

WATER AND THE THERMODYNAMICS OF BRINES

One prerequisite of life as we know it is the availability, at least temporarily, of liquid water and hence, the centrality of water in the definition of Special Regions on Mars. Finding 3-14 of the SR-SAG2 report states that pure[2] liquid water is currently possible on some areas of Mars for short periods of time. In particular, the report states that ". . . snow, however, has been detected on Mars (see Section 4.11). If snow melting yields liquid water on the surface of Mars, even periodically for only a short time, that water could be available for microbial use and define (for however short a time) a Special Region on Mars."[3] The review committee disagrees with this statement and, therefore, Finding 3-14. The fact that the surface pressure can be above that of the triple point simply indicates that water would not boil, not that liquid water would be stable. The review committee asserts that pure liquid water simply cannot exist on Mars because the atmosphere is too dry to allow it. The partial pressure of atmospheric water vapor is typically less than 1 Pa near the surface of Mars, whereas the partial pressure of water vapor at the triple point of water is about 600 Pa. Thus, even at the lowest temperature at which it could exist (the triple point), pure liquid water would evaporate and be cooled quickly, and therefore freeze quickly when exposed to the dry martian air, making pure liquid water near the triple point of water (above 0°C and below about 7°C; see in Figure 10 of the SR-SAG2 report).

Liquid brines (liquid water solutions), however, are possible on Mars (e.g., Fischer et al. 2014; Martín-Torres et al. 2015) because at low temperatures the saturation vapor pressure above them can be as low as the partial pressure of water vapor in the martian atmosphere. Therefore, the committee does not support Finding 3-14.

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[2] The committee uses the terminology pure water to draw a clear distinction between it (i.e., liquid H_2O) and aqueous solutions of mineral salts (i.e., liquid brines).

[3] SR-SAG2 report, pp. 907-908.

SR-SAG2 Finding 3-14: Mars average atmospheric pressure allows for liquid water when it exceeds that of the triple point of water, and at lower altitudes (e.g., Hellas and Argyre Basins) that is commonly the case. Higher temperatures and/or insolation may allow melting or condensation over limited areas for short time periods.

Not supported by the review committee.

The committee also proposes the following corrections to Figures 9 and 10 of SR-SAG2 report:

- In Figure 9, p/p_o at the top be replaced by a_w for the figure to be consistent with the text.
- There is a typo in the caption for Figure 9. The committee suggests that it read "as water is lost from the system between $a_w = 1.0$ (saturation) and $a_w = 0.9$ . . ."
- Figure 10 is missing the vertical line corresponding to 7°C and the horizontal line corresponding the maximum Mars surface atmospheric pressure referred to in Section 3.8.7 as "the narrow window above 608 Pa (0.006 atm) where pure liquid water can be stable when temperatures are above 0°C and below about 7°C." However, the committee does not agree with this statement because pure liquid water would be stable in this case only if the air were saturated. Stability implies that the water vapor partial pressure would have to be 608 Pa.

In addition, the committee proposes a revision to Finding 5-4, in order to expand the finding and include liquid aqueous solutions.

SR-SAG2 Finding 5-4: The mid-latitude mantle is thought to be desiccated, with low potential for the possibility of modern transient liquid water.

Revised Finding 5-4: The mid-latitude mantle is thought to be desiccated, with low potential for the possibility of modern transient liquid *aqueous solutions. However, a local detailed analysis for a particular area is necessary to determine if it could be a Special Region.*

DARK SLOPE STREAKS, RECURRING SLOPE LINEAE, AND GULLIES

Dark Slope Streaks

The recent discovery of "recurring slope lineae" (RSL) (McEwen et al. 2011) prompted the SR-SAG2 report to devote considerable attention to these surface features, which are found on steep, warm, rocky slopes. RSL extend and contract or fade in appearance on a seasonal cycle, suggestive of possible wetting and chemical precipitation. The review committee can accept SR-SAG2's Finding 4-1, as modified below, in that currently RSL may be caused by an aqueous process and, if true, may meet the criteria for an Uncertain Region, to be treated as a Special Region until proven otherwise. However, the committee disagrees with the statement "There are other features on Mars with characteristics similar to RSL, but their relationship to possible liquid water is much less likely" because the SR-SAG2 report does not indicate what is meant by "characteristics similar to RSL" and does not justify why "their relationship with possible liquid water (pure or saline solutions) is much less likely." Ongoing research suggests that RSL differ from at least some phenomena classed as "slope streaks" only because of their smaller size and shorter fading time (Mushkin et al. 2014a).

The SR-SAG2 report devoted minimal discussion to slope streaks, treating them as general phenomenon distinct from RSL, and did not cite recent research results that may suggest a continuum between the phenomena (Mushkin et al. 2014a). For example, Mushkin et al. (2014b) documented observations of some slope streaks with shorter formation and fading timescales than indicated in the SR-SAG2 report. They report seasonal change and incremental growth of slope streaks near Olympus Mons and Arabia Terra, in direct contrast to the SR-SAG2 report's generalization for the slope streaks as a phenomenon distinct from RSL. Moreover, recent analyses of the slopes on which slope streaks form suggest they do not have significant inertia that would be expected for dry granular flow (Brusnikin et al. 2015). Although Brusnikin et al. (2015) consider slope streaks to be different from RSL (in agreement with SR-SAG2), their results suggest that the formation of slope streaks is far from being understood. These results are sufficient to indicate that more attention needs to be devoted to understanding the relationships between the now intensely studied RSL and at least some of the much less well studied features that have been grouped into the general category of "slope streaks." Like RSL, it is advisable that these phenomena be documented on a case-by-case basis for the planned landing ellipse of specific missions, to demonstrate that they really are "dry dust avalanches" and not caused by aqueous processes. This review committee therefore suggests a slightly revised Finding 4-8.

> **SR-SAG2 Finding 4-8:** The 2006 Special Regions analysis did not consider dark/light slope streaks to be definitive evidence for water. Recent results have strengthened that conclusion for non-RSL slope streaks.

> **Revised Finding 4-8:** The 2006 Special Regions analysis did not consider dark/light slope streaks to be definitive evidence for *liquid (saline)* water. *Although some* recent results have strengthened that conclusion for non-RSL slope streaks, *other recent reports suggest that there are problems explaining all dark slope streaks by dry granular flow, and therefore aqueous processes cannot be definitely excluded for all dark slope streaks.*

Suggestions for future research directions relating to the issues discussed in this section can be found in Appendix A.

Specific Physical Conditions of Recurring Slope Lineae

Recurring slope lineae are narrow (<5 m wide), dark features that occur on steep (25°C to 40°C) slopes during warm seasons on low albedo surfaces (McEwen et al. 2011, 2014; Ojha et al. 2014). What is special about RSL is that they grow incrementally, can be more than 1 km long, and recur over several years. All confirmed RSL locations have warm daily peak temperatures (typically >273 K at the surface) during the seasons in which RSL are active (McEwen et al. 2011). These are not the characteristics that one would expect from flows of pure liquid water or liquid brines. Surface temperatures above 273 K would produce water vapor pressures above ~600 Pa, causing rapid evaporation and cooling of any pure liquid water or liquid brines exposed to the extremely dry martian air (atmospheric water vapor pressure <1 Pa). In fact, it follows from order-of-magnitude calculations that pure liquid water at 273 K exposed to the dry martian atmosphere would be subject to cooling rates of the order of 200 W/m^2 (of the order of the peak midday heating of the ground in the tropics) and evaporation rates of about 5 mm/Sol. The presence of liquid brines, instead of pure liquid water, would reduce evaporation and sublimation by no more than 50 percent, and it would be difficult to reconcile large evaporation rates with the long and narrow "wet" features of the RSL (e.g., Martínez and Rennó 2013). In addition, RSL originate near the top of steep slopes where subsurface water reservoirs are unlikely to exist. Moreover, RSL have the low thermal-inertial characteristics of loose regolith (compared to the surrounding terrain), not the higher thermal inertia expected from a wet regolith (Edwards and Piqueux 2015). The committee suggests rewording Finding 4-1.

> **SR-SAG2 Finding 4-1:** *Although* no single model currently proposed for the origin of RSL adequately explains all observations, *they are currently best interpreted as being* due to the seepage of water at >250 K, *with a_w unknown, and perhaps variable.* As such they meet the criteria for Uncertain Regions, *to be treated* as Special Regions. *There are other features on Mars with characteristics similar to RSL, but their relationship to possible liquid water is much less likely.*

> **Revised Finding 4-1:** No single model currently proposed for the origin of RSL adequately explains all observations. *However, there are suggestions that they are* due to the seepage of *liquid* water *(in some form)* at >250 K. As such, they meet the criteria for Uncertain Regions *and, together with slope streaks, be considered* as Special Regions. *However, a local detailed analysis for a particular area,*

based on the latest scientific information, is necessary to determine if it is to continue to be treated as a Special Region.

Gullies

Observations of gullies (Figure 3.3) over the past decade reveal occasional mass wasting and show that they are currently active. Because this present activity occurs when it is too cold for liquid water, it is likely that gullies can be reactivated, and possibly even be formed, by dry granular processes involving CO_2 frost as opposed to liquid water. Nevertheless, the exact origin of gullies is still unknown, and the debate whether liquid water is involved in certain stages of gully evolution continues. It may also be possible that gullies evolved during variable climate conditions and that both aqueous and dry CO_2-driven processes contributed to their present morphology. Although CO_2 is very likely responsible for the present-day activity seen in gullies, this does not preclude a former type of activity involving liquid water from being involved in their formation. Therefore, the review committee proposes a slight revision to Finding 4-2 to allow for the possibility that the formation of gullies and their present-day activity are driven by different processes.

SR-SAG2 Finding 4-2: Some martian gullies (Gully Type/Taxon 1) have been observed to be currently active, but at a temperature far too low to be compatible with the involvement of liquid water—a CO_2-related mechanism is implied in *their formation.*

Revised Finding 4-2: Some martian gullies (Gully Type/Taxon 1) have been observed to be currently active, but at a temperature far too low to be compatible with the involvement of liquid water—a CO_2-related mechanism is implied in *this current activity.*

POLAR DARK DUNE STREAKS

Polar dark dune streaks are a distinct class of active martian slope features that occur on dunes in both the north and south polar regions (Kereszturi et al. 2009, 2010). Möhlmann and Kereszturi (2010) argued that the streak morphologies and growth rates are consistent with viscous liquid flows, hypothesized to be concentrated brine. These features appear to develop as the regional temperatures slowly rise from their wintertime low at the CO_2 frost point (150 K). The SR-SAG2 report argues that this indicates that it is unlikely that these polar dunes streaks are brine flow because known brines are not liquid at temperatures below 200 K. However, Möhlmann (2010) shows that solid-state greenhouse effects can easily increase the upper subsurface temperature of snow and ice packs well above the eutectic temperature of salts known to exist on Mars. This could explain the formation of liquid brines in Mars' polar regions (Martinez et al. 2012; Martinez and Rennó 2013).

The presence of ice, likely in contact with salt particles, and the possibility of solid-state greenhouse effect (i.e., the warming of ice covered surfaces by the absorption of solar radiation and re-emission of infrared radiation) indicate that the formation of polar dune streaks could potentially involve liquid brines. Thus, to be conservative, the committee suggests revising Finding 4-9.

SR-SAG2 Finding 4-9: Polar dark dune streaks *are considered extremely unlikely to involve liquid water warmer than 253K (–20°C), and most likely do not involve liquid water at all, given the low surface temperatures present when they are active.*

Revised Finding 4-9: *A conservative interpretation of the evidence suggests that* polar dark dune streaks *could potentially involve liquid brines but only in the presence of heating mechanisms such as solid-state greenhouse effects.*

The discovery of soft, segregated ice in the shallow subsurface of Mars by NASA's Phoenix lander (Rennó et al. 2009; Cull et al. 2010) was unexpected and is not well understood yet. However, liquid brines could easily form in the polar region when perchlorate salts come into contact with ice, frost, or snow (Fischer et al. 2014). Moreover, liquid brines are far more likely to occur on Mars than pure liquid water. Thus, the committee suggests revising Finding 5-7.

SR-SAG2 Finding 5-7: We do not have accepted models *or tested hypotheses* to explain the *phenomenon of "excess"* ice on Mars. *It is not known whether this ice was produced in the past by a process involving liquid water, or whether it is an ongoing process.* The age of that ice and its implications for the next 500 years are unknown.

Revised Finding 5-7: We do not have accepted models to explain the *presence of segregated* ice on Mars *yet. However, a conservative interpretation of the evidence suggests that processes involving liquid brines (likely at temperatures below –25ºC) could have produced the segregated ice.* The age of that ice and its implications for the next 500 years are unknown.

Suggestions for future research directions relating to the issues discussed in this section can be found in Appendix A.

SHALLOW SUBSURFACE CONDITIONS AND ICE DEPOSITS

The committee suggests combining the SR-SAG2 report's Findings 4-6 and 4-7 into the Revised Finding 4-6/7 to eliminate ambiguities.

SR-SAG2 Finding 4-6: Within the bounds of several limitations of the MARSIS and SHARAD radar surveys (including attenuation, location-specific surface clutter, relatively low spatial resolution, saturated porosity, and areal coverage), groundwater has not been detected anywhere on Mars within ~200-300 m of the surface. This does not preclude the existence of groundwater at greater depths, *which should be considered as an Uncertain Region (and a potential Special Region) until further geophysical investigation proves otherwise.*

SR-SAG2 Finding 4-7: *We cannot rule out the possibility of* near-surface *water that may be present* at a vertical and/or horizontal scale finer than that detectable by MARSIS and SHARAD.

Revised Finding 4-6/7: Within the bounds of several limitations of the MARSIS and SHARAD radar surveys (including attenuation, location-specific surface clutter, relatively low spatial resolution, saturated porosity, and areal coverage), groundwater has not been detected anywhere on Mars within 200-300 m of the surface. This does not preclude the existence of groundwater at greater depths, *or* near-surface *groundwater* at a vertical and/or horizontal scale finer than that detectable by MARSIS and SHARAD.

In the review committee's opinion the statement in Section 4.9, the second paragraph of the SR-SAG2 report: "Ground-ice stability occurs when the annual mean vapor density over ice in the soil pore space, integrated over these seasonal cycles, equals that of the atmosphere (Mellon and Jakosky, 1993)" is not strictly correct. It represents only a first order approximation.

The statement in paragraph four of the same section, "The low amount of water in the atmosphere of Mars results in a very low relative humidity at the site when the temperatures approach the lower temperature limit for microbial cell division (255 K)," is not correct because over ice, in the shallow subsurface, the air in the soil pore space would be saturated (e.g., Rennó et al. 2009). Thus, even if the amount of water in the atmosphere is low, it could be high in the shallow subsurface where ground ice exists.

Suggestions for future research directions relating to the issues discussed in this section can be found in Appendix A.

DELIQUESCENCE

Section 4.10 of the SR-SAG2 report states that "in order to understand if, when, and where deliquescence may be occurring on Mars and under what conditions the resulting aqueous solutions may persist, we need to understand . . . the kinetic factors that may affect aqueous-phase formation and disappearance." This is an excellent point that needs to be emphasized because deliquescence *is strongly limited by kinetics*. Fischer et al. (2014) report that when water vapor is the only source of water, bulk deliquescence of the salts that have been discovered on Mars is not rapid enough to occur during the short periods of the day during which the ground temperatures are above the salts' eutectic temperatures. Only when the salts are in direct contact with water ice can bulk deliquescence occur in Mars environmental conditions. Thus, liquid aqueous solutions could form temporarily during diurnal cycles only where salts and ground ice co-exist in the shallow martian subsurface and on the surface when frost or snow are deposited on saline soils (Fischer et al. 2014).

The review committee suggests rewording Finding 4-14.

> **SR-SAG2 Finding 4-14:** *Natural deliquescence* of calcium perchlorate, the mineral with the lowest eutectic temperature relevant to Mars, *is predicted* for short periods of time each day at each of the three landing sites for Viking 1, Phoenix, and *MSL* (where we have measurements) and presumably at many other places on Mars.

> **Revised Finding 4-14:** *Liquid solutions* of calcium perchlorate, the mineral with the lowest eutectic temperature relevant to Mars, *could form* for short periods of time each day at each of the three landing sites for Viking 1, Phoenix, and *Mars Science Laboratory* (where we have measurements) and presumably at many other places on Mars *when water ice gets in contact with salt.*

A stable aqueous solution might form (not "will form" as stated in the second paragraph of Section 4.10 of the SR-SAG2 report, because on Mars deliquescence is strongly limited by kinetics) via deliquescence when the atmospheric relative humidity at the surface of a given salt is greater than or equal to the deliquescence relative humidity of that salt.

Figure 27 of the SR-SAG2 report shows a non-standard stability diagram plotted by relating the concentration of the solution with the relative humidity of the air just above it. Some of the labels in the diagram are ambiguous, and the figure caption and text are inconsistent with what are expected based on standard stability diagrams. According to these standard diagrams, aqueous salt solutions are possible whenever the temperature is above the eutectic value. Therefore, liquid brines are not rare. They are expected to form when ice gets into contact with salt whenever the temperature exceeds the eutectic value.

SNOW, ICE DEPOSITS, AND SUBSURFACE ICE

Fischer et al. (2014) report that when salts are in direct contact with water ice, bulk deliquescence occurs within minutes when the temperature exceeds the eutectic temperature of calcium perchlorate. The atmospheric water vapor content is not relevant in this case because $a_w = 1.0$ over the ice. This indicates that liquid aqueous solutions are likely to form temporarily when snow is deposited on saline soils. Thus, the review committee suggests revising Finding 4-16.

> **SR-SAG2 Finding 4-16:** Snow *may be* deposited in polar *or equatorial regions* and elsewhere, *although its volume is thought to be negligible. It* is expected to fall during the coldest part of the night and may *disappear (by sublimation or melting/evaporation/boiling) soon* after *the day begins on Mars. It is unknown whether this process could create a Special Region on Mars.*

> **Revised Finding 4-16:** Snow *is* deposited in *the* polar *region* and *might also be deposited in small amounts* elsewhere. *Snow* is expected to fall during the coldest part of the night *(when the ground temperature is*

below –25°C) and may *sublimate shortly* after *sunrise. However, snow could melt if deposited on salts with eutectic temperature lower than that at which sublimation occurs, possibly creating temporary Special Regions.*

There appears to be substantial subsurface ice on Mars, even in equatorial regions (e.g., Vincendon et al. 2010; Scanlon et al. 2015). For example, work by Vincendon et al. (2010) as well as theoretical modelling (see references in Vincendon et al. 2010) demonstrates that on pole-facing slopes at mid-latitudes and in the tropics ice can be at a depth of less than 5 m. The committee therefore suggest that Finding 5-3 be revised.

SR-SAG2 Finding 5-3: Depths to buried ice deposits in the tropics and mid-latitudes are considered to be >5 m.

Revised Finding 5-3*: In general,* depths to buried ice deposits in the tropics are considered to be >5 m. *However, there is evidence that water ice is present at depths of <1 m on pole-facing slopes in the tropics and mid latitudes. Thus, a local detailed analysis for a particular area is necessary to determine if it could be a Special Region.*

Finally, the committee proposes a small revision to Finding 5-9.

SR-SAG2 Finding 5-9: Mineral deliquescence on Mars may be triggered by the presence of a nearby spacecraft, or by the actions of a spacecraft.

Revised Finding 5-9: Mineral deliquescence *and the melting of ice* on Mars may be triggered by the presence of a nearby spacecraft, or by the actions of a spacecraft.

Suggestions for future research directions relating to the issues discussed in this section can be found in Appendix A.

CAVES AND SUBSURFACE CAVITIES

SR-SAG2 Finding 4-11: On Earth, special geomorphic regions such as caves can provide radically different environments from the immediately overlying surface environments providing enhanced levels of environmental protection for potential contaminating organisms. The extent of such geomorphic regions on Mars and their enhancement (if any) of habitability are currently unknown."

No change.

The committee generally concurs with Finding 4-11 which is related to caves on Mars. Although their number and sizes are largely unknown, caves and other subsurface cavities on Mars would represent environments with ambient conditions (e.g., temperature, humidity, exposure to radiation) that are very different from those at the surface, and most probably, those conditions are likely to be favorable for microbial colonization. Consideration of caves and subsurface cavities is paramount for two reasons. First, they provide a protected environment (e.g., from extremely low temperatures and radiation). Second, they can provide a means by which terrestrial contamination can access martian subsurface environments. In addition to drained lava tubes, voids resulting from tension fracturing, and possible caves in evaporites (e.g., gypsum karst), there are types of subsurface cavities on Mars not mentioned in the SR-SAG2 report that may have been produced by subsurface erosion by water (analogous to piping; e.g., Higgins and Coates 1990) or by expulsion of material through hydrothermalism (Rodríguez et al. 2005) or mud volcanism (Rodríguez et al. 2012). However, to the best of the review committee's knowledge, there is no data on the availability of water in martian caves.

The committee also concurs with the report's identification of specific knowledge gaps related to caves. Specifically, the actual number and location of potential caves on Mars is difficult to assess. Because current subsurface information (e.g., from radar) is insufficient to detect caves, their identification is only possible through a combination of high-resolution imaging and thermal data (Cushing 2012; Cushing et al. 2015; Jung et al. 2014; Lopez et al. 2012). Ground-based thermal observations by rovers may enable detection of accessible subsurface cavities that are too small to be detected from orbit (Groemer et al. 2014). ESA's Mars Trace Gas Orbiter may be able to identify point sources of potential anomalous gases released from the subsurface, as discussed earlier in this chapter (see "Methane: Potential Abiotic and Biotic Sources").

An important factor that could limit microbial metabolisms in any subsurface environment is adequate energy sources. Hydrogen can be produced by hydrolysis of olivine in basalts at relatively low temperatures (343 K) by carbonate-containing solutions (Neubeck et al. 2014). On Earth, many thermophiles, mainly archaea, live in this temperature range; hyperthermophiles live even at temperatures of up to 386 K (113°C). Nevertheless, in oligotrophic subsurface sediments, microbial enhancement of H_2 production from the alteration of minerals has been detected (Parkes et al. 2011). Thus, if H_2 could be liberated, corresponding electron acceptors might be Fe^{3+} (from mafic minerals in basalts); CO_2 from the atmosphere for metabolisms, such as hydrogenoclastic methanogenesis or the Wood-Ljungdahl pathway; or SO_4^{2-} for sulphate reduction, O_2, or halogens for dehalorespiration. Independently, all of these possible redox couples exist on Mars. Methane could be a source of electrons coupled to either O_2 or SO_4^{2-}—if clathrates have been breached. Organics, if present, could be coupled with Fe^{3+}, SO_4^{2-} or halogens. Fermentation reactions could take place with amino acids, organic acids and/or alcohols, or halogens. Thus, the review committee proposes a revision to Finding 2-1.

> **SR-SAG2 Finding 2-1:** Modern Mars environments may contain *molecular fuels and oxidants* that are *known to support metabolism and cell division of* chemolithoautotrophic microbes *on Earth.*

> **Revised Finding 2-1:** Modern Mars environments may contain *chemical compounds* that are *used as electron donors and electron acceptors by* chemolithoautotrophic microbes. *If organic compounds are also present on Mars, then heterotrophic microbes may also find a home there.*

In conclusion, there could be a number of possible primary sources of the necessary ingredients for life inside caves and subsurface cavities on Mars, and therefore, they are best classified as Uncertain Regions and treated as Special Regions until proven otherwise.

4

Human Spaceflight

Section 6 of the SR-SAG2 report addresses the implications and opportunities of the identification of Special Regions for human Mars missions. The review committee noted that the impact of human spaceflight on planetary protection, in general, and Special Regions, in particular, had not been considered with the same rigor and thoroughness that had been applied to other parts of the SR-SAG2 report. Even though planning for human missions to Mars is in its infancy, the committee believes than the planetary protection implications of sending astronauts to Mars raises profound questions at the intersection of science, engineering, technology, project management, and public policy. The committee recognizes that the SR-SAG2 report was not the place to address and/or resolve these issues. However, a greater emphasis that the issues exist was warranted.[1] Compounding this lack of emphasis, some statements made in the human exploration section of the SR-SAG2 report are inconsistent with other parts of the document. Examples of such inconsistencies include the following:

- The first sentence in Section 6.1.1 (Water resources) states: "The polar caps (between ~80° and 90° latitude in each hemisphere) would be the major reservoir of H_2O that can be accessed by human explorers and would not be considered to be Special Regions." This suggests that all locations in the polar cap will not be Special Regions. Sufficient examination of the polar cap has not been accomplished to support this statement. In addition, no mention is made of the possibility of Special Regions being induced by modification of the environment by spacecraft or human explorers.
- The second to last sentence in Section 6.1.1 states: "Therefore, other than the RSL sites and possibly active gullies, no location within the equatorial zone is considered Special." As identified above, sufficient examination of all locations within the equatorial region has not been accomplished to support this statement. In addition, the statement itself does not recognize other features such as caves and thermal zones identified within the report that may exist within this region. This can lead to misunderstandings by future mission planners who are considering missions to these areas.

[1] The committee notes that the planetary protection community has taken some initial steps to address issues relating to the human exploration of Mars. The website of the March 2015 meeting "Human Missions & Planetary Protection: Workshop on Planetary Protection Knowledge Gaps for Human Extraterrestrial Missions," http://planetaryprotection.nasa.gov/humanworkshop2015/, contains a useful summary of relevant issues and current activities.

Moreover, some of the language used to describe the systems required for human missions can be interpreted to mean that human missions will not be required to follow the COSPAR planetary protection requirements, even if in the actual COSPAR policy it is explicitly stated: "The intent of this planetary protection policy is the same whether a mission to Mars is conducted robotically or with human explorers. Accordingly, planetary protection goals should not be relaxed to accommodate a human mission to Mars" (COSPAR 2015, p. 14).

The review committee also noted that this section does not include any findings. This is inconsistent with earlier sections of the report and misses the opportunity to solidify the importance of the COSPAR planetary protection requirements. The committee proposes a finding for this section.

> ***New Finding 6-1:*** *Human missions to Mars are required to fully follow the planetary protection requirements specified by COSPAR, including the limitations specified for Special Regions. This may prevent humans from landing in or entering areas that may be Special Regions or may become Special Regions through modifications of the environment by space systems and/or human explorers.*

Finally the committee recognizes that human spaceflight systems operate differently than robotic systems. Understanding the implications of humans on Mars and the ability of human systems to meet COSPAR requirements is essential to ensuring that nations can continue to conduct science investigations without worrying that these human systems have contaminated places where science is being conducted.

Suggestions for future research directions relating to the issues discussed in this section can be found in Appendix A.

5

Generalization of Special Regions and the Utility of Maps

Figure 47 of the SR-SAG2 report plots the global distribution of confirmed and unconfirmed recurring slope lineae (RSL) with 50 km buffer zones around them (Figure 5.1). These buffer zones, the report argues, "provide for adequate precautions for spacecraft landings in their proximity, including an allowance for the possibility of an off-target landing (Figure 47)" (p. 943 of the SR-SAG2 report). This could be misinterpreted in the sense that a landing outside the areas shown in Figure 47 would definitely avoid RSL-related Uncertain or Special Regions, although the review committee is aware that this is certainly not the intention of the authors of the SR-SAG2 report. As RSL studies are a very active field of Mars research, it is expected that the number of fully and partially confirmed RSL will increase from now to the near future, just as it has increased from their first detection (McEwen et al. 2011) up to now (Dundas et al. 2015). Hence, the map displayed in Figure 47 represents only a snapshot in time and will probably be outdated soon. While it is helpful to provide a general overview of regions that may be favorable for the formation of RSL, it is of limited use in the identification of Uncertain or Special Regions. The same applies to other maps that also may be updated soon (e.g., Figures 45 and 46 of the SR-SAG2 report; see Figure 5.2).

Another potential source of misinterpretation related to the use of maps in Special Region studies is the issue of scale. Identification of a Special Region needs a multiscale approach (see also the discussion in Chapter 2, "Detectability of Potential Small Scale Microbial Habitats," and thus, as far as missions to Mars are concerned, conservatism demands that each landing ellipse be scrutinized on a case-by-case basis. Maps, which come necessarily at a fixed scale, can only provide information at that scale and are, therefore, generalizations. The review committee envisages that the case-by-case evaluation will follow a process analogous to that used to certify the landing sites for Schiaparelli—the entry, descent, and landing demonstrator on ESA's ExoMars 2016—and for NASA's InSight lander. In the case of Schiaparelli, for example, all available data for the proposed site in Meridiani Planum were analyzed to determine if Special Regions existed within the landing ellipse. In particular, all HiRISE images were inspected for the possible presence of RSL.

In general, the review committee contends that the use of maps to delineate regions with a lower or higher probability to host Special Regions is most useful if the maps are accompanied by cautionary remarks on their limitations. Maps that illustrate the distribution of specific relevant landforms or other surface features can only represent the current (and incomplete) state of knowledge for a specific time—knowledge that will certainly be subject to change or be updated as new information is obtained.

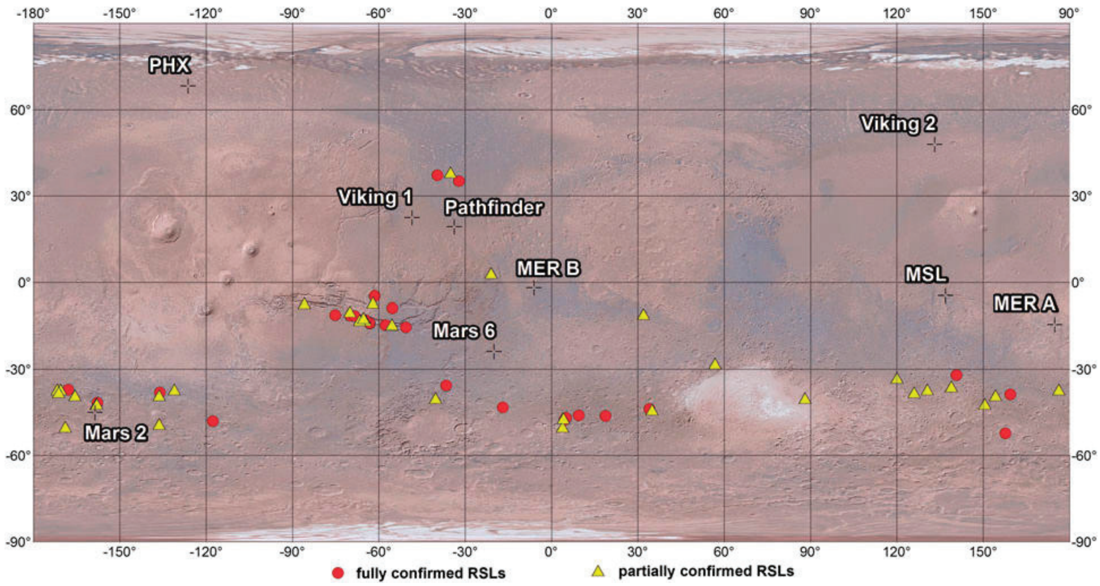

FIGURE 5.1 Locations of recurring slope lineae (RSL) on Mars, identified at the time of publication. Red circles indicate confirmed RSL, while yellow triangles represent partially confirmed RSL. RSL require high-resolution and time-series observations for initial identification. They may be the most significant candidate sites for Mars Special Regions. SOURCE: SR-SAG2 report (Rummel et al. 2014, Figure 47); courtesy of the Second MEPAG Special Regions Science Analysis Group.

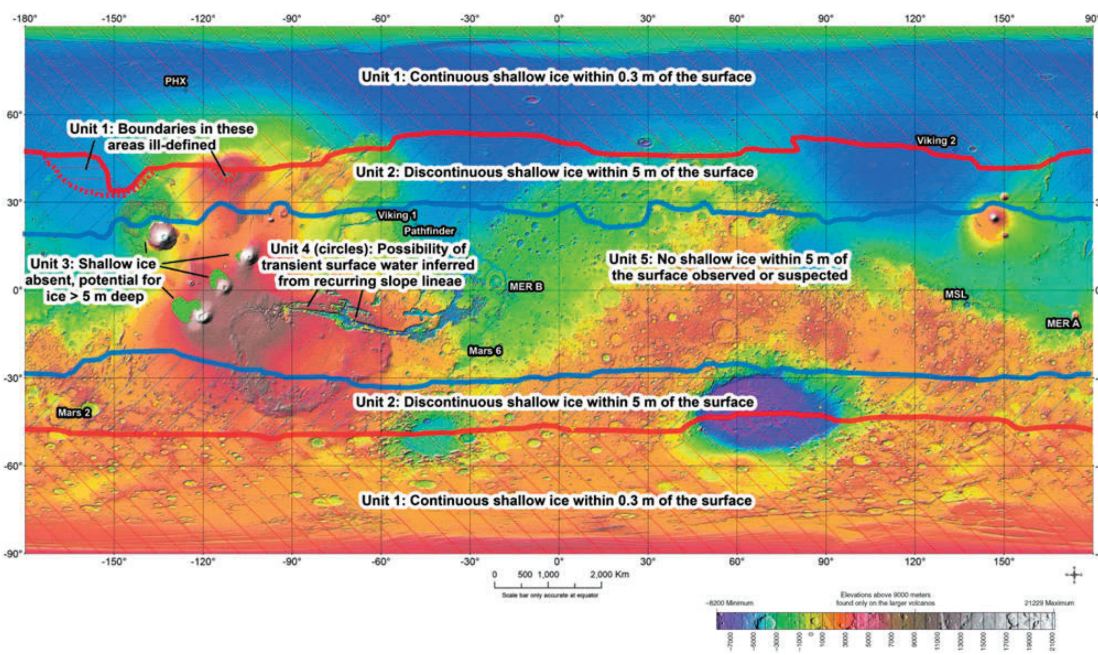

FIGURE 5.2 Map depicting geological features relevant to characterizing Special Regions on Mars. Indicated units describe shallow ground ice or potential transient surface water in terms of their depth below the surface and spatial continuity. The map base is MOLA digital elevation model of Mars (~463 m/pixel; Neumann et al. 2001) in simple cylindrical projection. Purple is low in elevation, and grey is higher elevation. Red and blue lines delineating regions are approximately 50 km in width. SOURCE: SR-SAG2 report (Rummel et al. 2014, Figure 45); courtesy of the Second MEPAG Special Regions Science Analysis Group.

Recommendation: Maps should only be used to illustrate the general concept of Special Regions and should not be used to delineate their exact location. Uncertain Regions in planned landing ellipses should be evaluated on a case-by-case basis as part of the site selection process. The goal of such an evaluation is to determine whether or not the landing ellipse contains water, ice, or subsurface discontinuities with a potential to contain hydrated minerals that could be accessed via a landing malfunction or by the operation of subsurface-penetrating devices (e.g., drills). As an example, landing site analysis will likely include a geological analysis, drawing on the Mars geologic literature (covering a broad range of relevant topics, including ground truth at previous lander locations) as well as orbital imaging, infrared spectroscopy, gamma-ray spectroscopy, and ground-penetrating radar sounding of the specific region.

6

Summary

The joint committee was asked to review the current planetary protection requirements for Mars Special Regions and their proposed revision as outlined in the SR-SAG2 report and to suggest updates to the planetary protection requirements for Special Regions. Based on its discussions and deliberations, the review committee organized its conclusions under the following five headings:

- Overall Assessment of the SR-SAG2 Report;
- Environmental Parameters Defining a Special Region;
- Identification of Special Regions;
- Specific Terrains Identified as Special Regions; and
- Updated Definition of a Special Region

OVERALL ASSESSMENT OF THE SR-SAG2 REPORT

The authors of the SR-SAG2 report are to be commended for their comprehensive review of the issues associated with Special Regions and the factors used to define them. The SR-SAG2 report contained 45 findings and the review committee supports 29 of them. The committee's assessments of the remaining 16 are detailed below:

- *Finding not supported*—The committee does not support Finding 3-14 of the SR-SAG2 report. The committee does not agree with the idea that that the atmospheric pressure on Mars is generally high enough "to allow any unfrozen (pure) water to exist as a liquid for short periods of time before it either evaporates or boils away" as suggested by Finding 3-14.
- *Finding supported in modified form*—The committee proposed revisions to several findings in order to eliminate ambiguities or incorporate some recent findings that were made after the SR-SAG2 report was written. In particular, the committee supports 13 in revised form (2-1, 2-4, 3-1, 4-1, 4-2, 4-8, 4-9, 4-14, 4-16, 5-3, 5-4, 5-7, and 5-9). In addition, the committee suggests that two findings (4-6 and 47) be combined. The committee notes that the proposed revisions to two of these findings (2-4 and 4-1) have a direct impact to the definition of a Special Regions.
- *New finding*—The committee proposes a new finding, with regard to human spaceflight, which will

strengthen future efforts to update planetary policy findings (i.e., the need to be explicit with regard to the limits of human exploration (6-1) and the need to update policy based upon the proposed revision to Finding 5-9.

The specific wording of all of the findings in the SR-SAG2 report and the review committee's revised and new findings can be found in Appendix B.

ENVIRONMENTAL PARAMETERS DEFINING A SPECIAL REGION

The review committee concluded that environmental parameters used to define Special Regions (currently in the COSPAR policy and agreed upon in the SR-SAG2 report) of temperature and water activity are still appropriate. However, the review committee believes that if the detection of methane in the martian atmosphere—which is almost certainly indicative of the presence of water and may indicate biogenic activity—is confirmed, that may demand that the source region—that is, the zone where methane is being produced—be designated as a Special Region.

IDENTIFICATION OF SPECIAL REGIONS

The review committee concluded that the identification of Mars Special Regions is problematic for several reasons. First, detailed knowledge of the physical and chemical conditions of the surface and sub-surface of Mars at various scales is lacking, particularly the microscale. Second, current understanding of the ability of life to propagate is limited. It is not known if one, ten, or a million cells from a single species are required for propagation in an extraterrestrial environment. Alternatively, propagation may only be possible for microbial communities (i.e., collections of many different species). In view of the rapid development of powerful new techniques in biology and the increase in knowledge of the martian environment by ongoing and future space missions, the current practice of reassessing the concept of a Special Region and its definition every 2 years is both appropriate and essential.

SPECIFIC TERRAINS IDENTIFIED AS SPECIAL REGIONS

The specific terrains identified as Special Regions in both the COSPAR policy and in the SR-SAG2 report (i.e., "gullies, and bright streaks associated with gullies, pasted-on terrains, subsurface below 5 meters, others, to be determined, including dark streaks, possible geothermal sites, fresh craters with hydrothermal activity, modern outflow channels, or sites of recent seismic activity" and "spacecraft-induced Special Regions") are best regarded as "Uncertain Regions." The final determination of a Special Region would depend on the review of the latest scientific knowledge about a specific site in order to verify if it is within the environmental parameters defining Special Regions, taking into consideration the potential existence of microscale habitats.

UPDATED DEFINITION OF A SPECIAL REGION

Based on its discussions and deliberations, the review committee proposes an update to the definition of a Special Region (COSPAR 2015). The proposed changes are based on the critical new findings the committee identified that have a direct bearing on the designation of Special Regions. Two of the critical new findings came to the fore because of reconsideration of the relevance of methane to planetary protection (see Revised Finding 2-4) and the realization that recurring slope lineae are best treated as Uncertain Regions (see Revised Finding 4-1).

Given current understanding of terrestrial organisms, Special Regions are defined as areas or volumes within which sufficient water activity AND sufficiently warm temperatures to permit replication of Earth organisms may exist. The physical parameters delineating applicable water activity and temperature thresholds are given below:

- Water activity: lower limit, 0.5; upper limit, 1.0;
- Temperature: lower limit, –25°C; no upper limit defined; and
- Timescale within which limits can be identified: 500 years.

Observed features for which there is a significant (but still unknown) probability of association with liquid water, and which should be considered as Uncertain Regions and treated as Special Regions until proven otherwise

- Sources of methane (if identified);
- Recurring slope lineae;
- Gullies and bright streaks associated with gullies;
- Pasted-on terrains;
- Caves, subsurface cavities, and subsurface below 5 meters; and
- Others, to be determined, including dark slope streaks, possible geothermal sites, fresh craters with hydrothermal activity, modern outflow channels, or sites of recent seismic activity.

Spacecraft-induced special regions are to be evaluated, consistent with these limits and features, on a case-by-case basis.

Organizations proposing to investigate any region that may meet the criteria above, have the responsibility to demonstrate, based on the latest scientific evidence and mission approach, whether or not their proposed landing sites are or are not Special Regions.

In the absence of specific information, no Special Regions are currently identified on the basis of possible martian life forms. If and when information becomes available on this subject, Special Regions will be further defined on that basis.

7

Additional Considerations

The committee's review of the SR-SAG2 report mainly focused on the scientific basis of the detailed assignment of the Special Region status to specific geomorphologies associated with the accumulation of water/ice and fluid flows. While the committee mostly concurred with those findings, it noted the lack of discussion in the SR-SAG2 report on the likeliness of Earth microbes thriving in Special Regions. The discussion presented in Chapter 2 of this report provides additional biological considerations (e.g., production of EPS in natural communities of microbes) that show the high flexibility by microbial communities in propagating in harsh conditions. However, the SR-SAG2's analysis does not attempt to calculate or weigh the probability of any contaminating microbes from a spacecraft cleanroom on Earth actually surviving and growing in each of the newly assigned Mars Special Regions. Propagation of contaminant life from Earth on Mars on a large scale, in addition to water and temperature, will need redox gradients of abundant electron donors and acceptors for chemolithotrophic bacteria or metabolites that other microbes might use. For such a community to transplant to Mars, the co-dependent members must survive the transit to Mars and all thrive in the new Mars environment.

On analysis, it became clear to the committee that many of the planetary protection measures are ultimately derived from probability calculations undertaken for the Viking missions in the mid-1970s. In the 45 years since the first calculations for planetary protection were made, the science of microbiology has advanced dramatically. The advancements and innovations in technology in the post-genomic era of biology warrant reconsideration of the basic science behind many of the assumptions that underpin current thinking about planetary protection policy.

In the past century, the bioburden limits were defined in the implementation guidelines of the COSPAR planetary protection policy and are still valid. They are based on a specific cultivation assay after a heat treatment of each sample. According to the general opinion at that time, only very resistant microbes in the form of bacterial spores are detected by this assay, and only these seemed to be relevant for Mars because they might be able to survive there. However, the definition of Special Regions specifically refers to the ability of organisms to multiply, not just survive. The spores enumerated with the standard planetary protection bioburden assay are heterotrophic mesophilic aerobes. This type of organism could survive under certain circumstances on Mars, but they cannot multiply there due to the generally low temperatures, the lack of oxygen in the atmosphere, and insufficient concentrations of organic compounds for metabolism.

At the time the standard assay was developed, extremophiles, among them many thermophilic and hyperthermophilic archaea and bacteria, were not yet discovered. In the intervening years, researchers have learned that the majority of microbes are not cultivable and that several extremophiles that do not form spores are, nevertheless, resistant to many extreme environmental conditions. Therefore, the applied bioburden measurements detecting only a very small portion of the present microbes can only be seen as a proxy for the overall bioburden.

The committee is of the opinion that bioburden assays have to be modified to give more relevant information about non-spore forming microbes with the physiological potential to survive and even replicate on Mars taking the new molecular based methods into consideration.

Suggestions for future research directions can be found in Appendix A.

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Appendixes

A

Suggestions for Future Research

The review committee's statement of task (see Preface) did not call for recommendations for future research to reduce uncertainties surrounding the various issues and questions discussed in its report. Nevertheless, the committee was verbally encouraged to do so by the planetary protection officers from NASA and ESA. In the absence of a formal request for specific research recommendations, the review committee has limited itself to providing suggestions for future research. These suggestions are open ended and are not comprehensive. They are not directed at any particular organization or group and are unlikely to provide new insights or information on a timescale that will impact the Mars missions currently in development. Moreover, since they were not formally requested, they are not developed in any detail and contain few, if any, specifics. Nevertheless, the review committee believes that they represent a good starting point for any future group chartered to study Special Regions and issue formal recommendations.

It will be noted that the research directions identified below cover topics of interest to astrobiologists, planetary scientists, and planetary protection practitioners. The casual reader may ask where do astrobiology or planetary science end and planetary protection begin. The review committee does not recognize these disciplinary distinctions: at best they are just different approaches to addressing fundamental questions—such as, are we alone in the universe—in a scientifically responsible manner. In that spirit, we propose the following suggestions for future research in order to shed light on issues identified during the review process:

Investigations of the Limits of Life on Earth

- Undertake standardized laboratory investigations with microbial communities to analyze their responses to environmental stressors in general. Examples include the effects of low temperatures, temperature cycles around the freezing point, low pressure, Mars-like atmosphere, low water activity, periods of complete desiccation, oligotrophic nutrient media, periods of starvation, exposure to ionizing radiation, and exposure to Mars-like polychromatic ultraviolet radiation.
- Undertake long-term investigations of psychrophilic microbial isolates and psychrophilic microbial communities to determine the lower temperature and water-activity limit for replication and analyze the effect of chaotropic compounds on these limits.

- Investigate the potential capability of microbial isolates and microbial communities to divide if water is only present in the form of water vapor over the full temperature range for which microorganisms are known to replicate.
- Investigate the potential of microbial isolates and microbial communities to use liquid water in thin films on mineral grains as their sole source of water for replication.

Life in Extreme Environments and in Multispecies Communities

- Investigate the effects of successively and simultaneously applied multiple Mars-relevant environmental stress factors on microbial isolates and microbial communities to improve understanding of the mechanisms of adaptation, the evolutionary process whereby an organism becomes better able to live in habitats subject to extreme environmental conditions.
- Undertake experiments to determine the minimum threshold of microbial isolates and microbial communities found in spacecraft assembly facilities and on spacecraft that can establish a community in a simulated Mars Special Region.
- Undertake in situ mapping of the microheterogeneity of biologically important environmental parameters in the landing ellipse of a future space mission dedicated to astrobiology.
- Understand the role and selective advantage of the biofilm form of life in more depth, with emphasis on the tolerance to Mars-relevant stressors (e.g., desiccating conditions, low water availability, low temperature, high fluences of biologically effective ultraviolet radiation, ionizing radiation.

Detectability of Potential Small-Scale Microbial Habitats

- Perform in situ investigations in extreme environments on Earth to deepen our knowledge about microbial processes and habitability at micron scales. Adapt and optimize existing technologies and develop new ones to undertake the kind of investigations which may be used in the future exploratory missions to other planets and moons of astrobiological relevance.

Translocation of Terrestrial Contamination

- Undertake investigations of transport mechanisms and microbial viability in Mars simulation chambers—e.g., the Mars Surface Wind Tunnel facility at NASA's Ames Research Center or the low-pressure recirculating wind tunnels in the Mars Simulation Laboratory at Aarhus University—wherein microbes and spores are exposed to Mars-relevant levels of ultraviolet radiation, desiccation, nutrient deficit, and air movement, to assess the likelihood of survival during transport by, for example, dust storms.

Methane: Potential Abiotic and Biotic Sources

- Study the possible source and/or reservoirs of active methane release on Mars to identify the mechanism(s) responsible for producing and/or releasing it to the martian atmosphere. The ExoMars Trace Gas Orbiter could potentially acquire data that are essential to address this problem.

Dark Slope Streaks and RSL

- Study the formation of RSL and the class of dark slope streaks that shares similarities to RSL. It would be especially important to devise laboratory experiments and better tests of the "dry" and "wet" hypothesis for the formation of these features.

Polar Dark Dune Streaks

- Research to address the formation of liquid brines and segregated ice in the polar regions. It would be particularly important to conduct laboratory experiments to study these processes.

Shallow Subsurface Conditions and Ice Deposits

- Studies to address the formation of liquid brines on past and future landing sites, the kinetic factors involved, and their implication for microbial growth.

Snow, Ice Deposits, and Subsurface Ice

- Research addressing the range of conditions in which liquid brines could form and be temporarily stable on the surface and shallow subsurface of Mars.

Human Spaceflight

- Conduct research and related activities to understand the implications of landing and operating human systems on Mars in a manner consistent with COSPAR planetary protection policy.

Additional Considerations

- Research to develop new bioburden assays for microbes with a high probability to survive in the martian environment. Assays taking into account the latest detection technologies and the specific requirements, restrictions, and practicalities imposed by the assembly, integration, and testing of space hardware are required.

B

MEPAG SR-SAG2 Findings, Revisions, and Updates

Table B.1 lists the SR-SAG2 report findings and indicates if a finding was accepted, complemented, or rephrased by the committee; revised text is shown in italics.

TABLE B.1 Comments, Revisions, and Updates to the SR-SAG2 Findings

SR-SAG2 Report Finding	Status
Finding 1-1: Modeling results predict that the conditions on Mars are in general slowly warming, but that the mean martian surface temperatures are not expected to increase by more than 0.2 K over the next 500 years.	No change.
Finding 2-1: Modern Mars environments may contain *molecular fuels and oxidants* that are *known to support metabolism and cell division of* chemolithoautotrophic microbes *on Earth*.	**Revised Finding 2-1:** Modern Mars environments may contain *chemical compounds* that are *used as electron donors and electron acceptors by* chemolithoautotrophic microbes. *If organic compounds are also present on Mars, then heterotrophic microbes may also find a home there*.
Finding 2-2: We cannot definitively rule out any terrestrial microbial taxon from being included in the potential "passengers" on a spacecraft to Mars.	No change.
Finding 2-3: Notwithstanding extensive spacecraft biodiversity studies, it is necessary for this analysis to use knowledge drawn from all Earth organisms, and not from only a currently identified subset or "passenger list."	No change.
Finding 2-4: Organic compounds are present on Mars (or in the martian subsurface); although in very low concentrations in samples studied to date. *Such detections are not used to distinguish Special Regions on Mars.*	**Revised Finding 2-4:** Organic compounds are present on Mars (or in the martian subsurface); although in very low concentrations in samples studied to date. *Abiotic or potentially biotic processes can explain the detection of episodic plumes of methane at various latitudes. In both cases, liquid water solutions would be involved. Therefore, the source regions of methane are considered as Uncertain Regions, even if the methane production is abiotic.*

TABLE B.1 Continued

SR-SAG2 Report Finding	Status
Finding 3-1: Cell division by Earth microbes has not been reported below –18°C (255 K).	**Revised Finding 3-1:** Cell division by Earth microbes has not been reported below –18°C (255 K). *The very low rate of metabolic reactions at low temperature result in doubling times ranging from several months to year(s). Current experiments have not been conducted on sufficiently long timescales to study extremely slow-growing microorganisms.*
Finding 3-2: Cellular metabolic activity has not been demonstrated below –33°C (240 K), although some biophysical processes may be functional at lower temperatures.	No change.
Finding 3-3: Chaotropic compounds can lower the temperature limit for cell division below that observed in their absence. There exists the possibility that chaotropic substances could decrease the lower temperature limit for cell division of some microbes to below –18°C (255 K), but such a result has not been published.	No change.
Finding 3-4: There is no evidence of either cell division or metabolism taking place in Earth organisms below an a_w of 0.60.	No change.
Finding 3-5: The amount of O_2 found in the martian atmosphere today has been shown to be sufficient to support the growth of some aerobic microorganisms on Earth—although this fact is not used to distinguish Special Regions on Mars.	No change.
Finding 3-6: Most Earth bacteria tested fail to grow below 2,500 Pa. However, a small subset of bacteria have now been identified that can reproduce (on rich hydrated agar media) in a “Mars” atmosphere (anoxic, CO_2) at average Mars pressure (700 Pa) and 0°C. This fact is not used to distinguish Special Regions on Mars.	No change.
Finding 3-7: The Mars ultraviolet radiation environment is rapidly lethal to unshielded microbes, but can be attenuated by global dust storms, and shielded completely by <1 mm of regolith or by other organisms.	No change.
Finding 3-8: From MSL RAD measurements, ionizing radiation from GCR at Mars is so low as to be negligible. Intermittent Solar Particle Events (SPE) can increase the atmospheric ionization down to ground level and increase the total dose, but these events are sporadic and last at most a few (2-5) days. These facts are not used to distinguish Special Regions on Mars.	No change.
Finding 3-9: The effects on microbial physiology of more than one simultaneous environmental challenge are poorly understood. Communities of organisms may be able to tolerate simultaneous multiple challenges more easily than individual challenges presented separately. What little is known about multiple resistance does not affect our current limits of microbial cell division or metabolism in response to extreme single parameters.	No change.
Finding 3-10: Determining the continuity/heterogeneity of microscale conditions over time and space is a major challenge to interpreting when and where Special Regions occur on Mars.	No change.
Finding 3-11: Some Earth organisms (lichens) can conduct metabolism (net photosynthesis) by using water vapor as their only source of water (at a relative humidity as low as ~70%, specifically with algal photobionts).	No change.

continued

TABLE B.1 Continued

SR-SAG2 Report Finding	Status
Finding 3-12: We have not found definitive evidence that any terrestrial organism can utilize ambient humidity alone to achieve cell reproduction. In experiments published and examined to date, liquid water is needed at some point in an organism's life cycle to reproduce. Nonetheless, there does not appear to be a fundamental barrier to microbial reproduction under these conditions.	No change.
Finding 3-13: Although the existence of thin films on grains in the shallow subsurface are predicted, they are not interpreted to be habitable by Earth microbes under the environmental conditions currently on Mars.	No change.
Finding 3-14: Mars average atmospheric pressure allows for liquid water when it exceeds that of the triple point of water, and at lower altitudes (e.g., Hellas and Argyre Basins) that is commonly the case. Higher temperatures and/or insolation may allow melting or condensation over limited areas for short time periods.	**Not supported by the review committee.**
Finding 3-15: a) Some environments support microsites where fluid can be trapped and retained preferentially for longer than is predictable on the basis of simple volatile behavior in the bulk environment, and b) some microorganisms have mechanisms that enable them to retain liquid water. Either situation could slightly widen the zone within which habitable temperatures may overlap the time during which available trapped water may be present and usable by organisms.	No change.
Finding 4-1: *Although* no single model currently proposed for the origin of RSL adequately explains all observations, *they are currently best interpreted as being* due to the seepage of water at >250 K*, with* a_w *unknown, and perhaps variable*. As such they meet the criteria for Uncertain Regions, *to be treated as* Special Regions. *There are other features on Mars with characteristics similar to RSL, but their relationship to possible liquid water is much less likely.*	**Revised Finding 4-1:** No single model currently proposed for the origin of RSL adequately explains all observations. *However, there are suggestions that they are* due to the seepage of *liquid* water *(in some form)* at >250 K. As such, they meet the criteria for Uncertain Regions *and, together with slope streaks, be considered* as Special Regions. *However, a local detailed analysis for a particular area, based on the latest scientific information, is necessary to determine if it is to continue to be treated as a Special Region.*
Finding 4-2: Some martian gullies (Gully Type/Taxon 1) have been observed to be currently active, but at a temperature far too low to be compatible with the involvement of liquid water—a CO_2-related mechanism is implied in *their formation*.	**Revised Finding 4-2:** Some martian gullies (Gully Type/Taxon 1) have been observed to be currently active, but at a temperature far too low to be compatible with the involvement of liquid water—a CO_2-related mechanism is implied in *this current activity*.
Finding 4-3: Some martian gullies appear to have formed by the melting of past water ice (Gully Type/Taxon 2). In cases where ice no longer remains, there is negligible potential for the presence of liquid water during the next 500 years. However, in circumstances where residual ice still remains, there is some potential for liquid water to be present there during the next 500 years.	No change.
Finding 4-4: It is possible for young, large craters to retain enough impact generated heat so that impact-caused hydrothermal activity would persist to the present. Although crater formation ages are highly uncertain, we have not identified any existing craters that have the combination of size and youthfulness necessary for this to be found today.	No change.

TABLE B.1 Continued

SR-SAG2 Report Finding	Status
Finding 4-5: Outflow channel events seen in the martian geologic record, but are incompletely understood. They may have resulted from the breeching of an existing reservoir of groundwater or may have been created by the melting of ground ice due to a rapid and localized heating of the crust. Based on the observed geologic record, they are rare and unpredictable, and unlikely to happen within the next 500 years.	No change.
Finding 4-6: Within the bounds of several limitations of the MARSIS and SHARAD radar surveys (including attenuation, location-specific surface clutter, relatively low spatial resolution, saturated porosity, and areal coverage), groundwater has not been detected anywhere on Mars within ~200-300 m of the surface. This does not preclude the existence of groundwater at greater depths, *which should be considered as an Uncertain Region (and a potential Special Region) until further geophysical investigation proves otherwise*. **Finding 4-7:** *We cannot rule out the possibility of* near-surface water *that may be present* at a vertical and/or horizontal scale finer than that detectable by MARSIS and SHARAD.	**Revised Finding 4-6/7:** Within the bounds of several limitations of the MARSIS and SHARAD radar surveys (including attenuation, location-specific surface clutter, relatively low spatial resolution, saturated porosity, and areal coverage), groundwater has not been detected anywhere on Mars within 200-300 m of the surface. This does not preclude the existence of groundwater at greater depths, *or* near-surface *groundwater* at a vertical and/or horizontal scale finer than that detectable by MARSIS and SHARAD.
Finding 4-8: The 2006 Special Regions analysis did not consider dark/light slope streaks to be definitive evidence for water. Recent results have strengthened that conclusion for non-RSL slope streaks.	**Revised Finding 4-8:** The 2006 Special Regions analysis did not consider dark/light slope streaks to be definitive evidence for *liquid (saline)* water. *Although some* recent results have strengthened that conclusion for non-RSL slope streaks, *other recent reports suggest that there are problems explaining all dark slope streaks by dry granular flow, and therefore aqueous processes cannot be definitely excluded for all dark slope streaks*.
Finding 4-9: Polar dark dune streaks *are considered extremely unlikely to involve liquid water warmer than 253 K (–20°C), and most likely do not involve liquid water at all, given the low surface temperatures present when they are active*.	**Revised Finding 4-9:** *A conservative interpretation of the evidence suggests that* polar dark dune streaks *could potentially involve liquid brines but only in the presence of heating mechanisms such as solid-state greenhouse effects*.
Finding 4-10: Over a decade of thermal IR mapping by the THEMIS instrument has not resulted in the detection of any local hot spots or warm zones that may represent a geothermal zone, at 100 m spatial resolution.	No change.
Finding 4-11: On Earth, special geomorphic regions such as caves can provide radically different environments from the immediately overlying surface environments providing enhanced levels of environmental protection for potential contaminating organisms. The extent of such geomorphic regions on Mars and their enhancement (if any) of habitability are currently unknown.	No change.
Finding 4-12: Environmental conditions at the Phoenix site, both at the surface (measured) and in the regolith (modeled) are incompatible with cell division. Note, however, that both sufficient water activity (as a vapor) and warmer temperatures may be present in the summer within the same 24-hour cycle, but never simultaneously.	No change.
Finding 4-13: Variations in inferred brine chemistry cannot at present be used in Special Regions analysis—there is not currently the means to predict or map different brine compositions on Mars.	No change.

continued

TABLE B.1 Continued

SR-SAG2 Report Finding	Status
Finding 4-14: *Natural deliquescence* of calcium perchlorate, the mineral with the lowest eutectic temperature relevant to Mars, *is predicted* for short periods of time each day at each of the three landing sites for Viking 1, Phoenix, and *MSL* (where we have measurements) and presumably at many other places on Mars.	**Revised Finding 4-14:** *Liquid solutions* of calcium perchlorate, the mineral with the lowest eutectic temperature relevant to Mars, *could form* for short periods of time each day at each of the three landing sites for Viking 1, Phoenix, and *Mars Science Laboratory* (where we have measurements) and presumably at many other places on Mars *when water ice gets in contact with salt*.
Finding 4-15: The environmental conditions associated with deliquescence at the MSL, Phoenix, and Viking 1 landing sites are all significantly outside the boundaries of the conditions required for reproduction of terrestrial organisms.	No change.
Finding 4-16: Snow *may be* deposited in polar *or equatorial regions* and elsewhere, *although its volume is thought to be negligible*. *It* is expected to fall during the coldest part of the night and may *disappear (by sublimation or melting/evaporation/boiling) soon* after *the day begins on Mars*. *It is unknown whether this process could create a Special Region on Mars*.	**Revised Finding 4-16:** Snow *is* deposited in *the* polar *region* and *might also be deposited in small amounts* elsewhere. *Snow* is expected to fall during the coldest part of the night *(when the ground temperature is below –25°*C*)* and may *sublimate shortly* after *sunrise*. *However, snow could melt if deposited on salts with eutectic temperature lower than that at which sublimation occurs, possibly creating temporary Special Regions*.
Finding 5-1: Thermal perturbation of the local environment by a spacecraft could induce localized Special Regions.	No change.
Finding 5-2: Tropical mountain glacial deposits may contain residual ice. However, these deposits are interpreted to be covered with an ice-free sublimation lag that is > ~5 m in thickness.	No change.
Finding 5-3: Depths to buried ice deposits in the tropics and mid-latitudes are considered to be >5 m.	**Revised Finding 5-3**: *In general*, depths to buried ice deposits in the tropics are considered to be >5 m. *However, there is evidence that water ice is present at depths of <1 m on pole-facing slopes in the tropics and mid latitudes. Thus, a local detailed analysis for a particular area is necessary to determine if it could be a Special Region.*
Finding 5-4: The mid-latitude mantle is thought to be desiccated, with low potential for the possibility of modern transient liquid *water*.	**Revised Finding 5-4**: The mid-latitude mantle is thought to be desiccated, with low potential for the possibility of modern transient liquid aqueous *solutions. However, a local detailed analysis for a particular area is necessary to determine if it could be a Special Region.*
Finding 5-5: Fresh ice exposed by impacts indicates the widespread presence of shallow ground ice at mid- and high latitudes—in many cases nearly pure ice, but displaying geographic heterogeneity.	No change.
Finding 5-6: The presence of polygonal ground at a candidate landing site may indicate a spacecraft-inducible Special Region by virtue of shallow ground ice, particularly when taken together with other observations indicating ice.	No change.

TABLE B.1 Continued

SR-SAG2 Report Finding	Status
Finding 5-7: We do not have accepted models *or tested hypotheses* to explain the *phenomenon of "excess"* ice on Mars. *It is not known whether this ice was produced in the past by a process involving liquid water, or whether it is an ongoing process*. The age of that ice and its implications for the next 500 years are unknown.	**Revised Finding 5-7:** We do not have accepted models to explain the *presence of segregated* ice on Mars *yet. However, a conservative interpretation of the evidence suggests that processes involving liquid brines (likely at temperatures below –25°C) could have produced the segregated ice*. The age of that ice and its implications for the next 500 years are unknown.
Finding 5-8: SHARAD has detected subsurface ice at scattered locations in the mid-latitudes.	No change.
Finding 5-9: Mineral deliquescence on Mars may be triggered by the presence of a nearby spacecraft, or by the actions of a spacecraft.	**Revised Finding 5-9:** Mineral deliquescence *and the melting of ice* on Mars may be triggered by the presence of a nearby spacecraft, or by the actions of a spacecraft.
Not addressed in the SR-SAG2 report.	***New Finding 6-1:*** *Human missions to Mars are required to fully follow the planetary protection requirements specified by COSPAR, including the limitations specified for Special Regions. This may prevent humans from landing in or entering areas that may be Special Regions or may become Special Regions through modifications of the environment by space systems and/or human explorers.*

C

Glossary

Abiotic: Of or relating to nonliving things; independent of life or living organisms.

Albedo: The fraction of light that is reflected by a surface; commonly used in astronomy to describe the reflective properties of planets, satellites, and asteroids.

Amino acid: Any organic compound containing an amino (NH_2) and a carboxyl (COOH) group. There are 20 α-amino acids from which proteins are synthesized during ribosomal translation of mRNA.

Anaerobe: An organism that can survive and reproduce in the absence of dissolved oxygen, instead using oxidants such as iron and sulfur compounds in energy metabolism.

Aqueous: Of or containing water, typically as a solvent or medium.

Archaea (Archaebacteria): Organisms making up one of the three branches on the phylogenetic tree of life. Their cells do not contain a defined nucleus, and they are genetically and biochemically distinct form the Bacteria. See **Bacteria**.

Back contamination: The biological contamination of Earth by possible life forms that may be returned from other solar system bodies.

Bacteria: Organisms making up one of the three branches on the phylogenetic tree of life. Their cells do not contain a defined nucleus, and they are genetically and biochemically distinct form the Archaea. See **Archaea.**

Basalt: A volcanic rock composed largely of plagioclase, feldspar, and dark minerals such as pyroxene and **Olivine**. A common surface rock on Mars. Thought to be the material from which martian soils were formed.

Bioburden assay: A test that measures the total number of viable microorganisms on an instrument. This number is used to determine the most appropriate parameters for its final sterilization.

Biofilm: An aggregate of microbes with a distinct architecture.

Biotic: Of or relating to living things; caused or produced by living organisms.

Brine: A solution of mineral salt in water.

Calcium perchlorate: The mineral with the lowest **eutectic temperature** relevant to Mars. See **Eutectic**.

Chaotropic compound: A molecule in water solution that can disrupt the hydrogen bonding network between water molecules. This affects the stability of other molecules in the solution, mainly macromolecules (nucleic acids, proteins), by weakening the hydrophobic effect.

Chemolithoautotroph: An organism deriving all of its carbon and energy requirements from inorganic compounds. The "litho" component of the name implies that the organism derives energy from minerals via, for example, the oxidation of hydrogen.

Clathrate: A compound in which one component is enclosed in a cage-like structure of another compound.

COSPAR: Committee on Space Research.

Cryopeg: A layer of unfrozen ground that forms a permanent part of the **permafrost**. See **Permafrost.**

Cryoprotectant: A substance used to protect biological surfaces from freezing damage.

Cryosphere: Near-surface, frozen layer including ground ice and **permafrost**. See **Permafrost.**

Cyanobacteria (Blue-green algae): A phylum of bacteria that obtain their energy through photosynthesis.

Dehalorespiration: Anaerobic respiration in some bacterial species that eliminates one or more halide atoms from halogenated compounds to yield energy for growth.

Deliquescent: Becoming or having the tendency to become liquid.

Desiccation: The state of extreme dryness, or the process of extreme drying.

EPS: Extrapolymeric substances. See **Extrapolymeric substances**.

Eutectic, value/temperature: The lowest possible melting temperature of a mixture of substances. This melting temperature is lower than that of any of the constituent substances and of any other mixture composed of the same constituents in different proportions.

Extrapolymeric substances (EPS): Compounds secreted by microorganisms into their environment consisting primarily of carbohydrates with some proteins, lipids, and DNA. EPS establish the functional and structural integrity of **biofilms**. See **Biofilm**.

Extremophile: A microorganism capable of growing under extreme physical and chemical conditions such as high temperatures, pressures, and acidity.

Forward contamination: The biological contamination of an extraterrestrial body by terrestrial organisms inadvertently carried aboard a spacecraft.

Halogens: A group on the periodic table consisting of five chemically related elements (fluorine, chlorine, bromine, iodine, astatine), which are missing one valence electron.

Halophilic: Requiring a high salt concentration for optimal growth.

Horizontal gene transfer: Exchange of genetic material that occurs without direct cell-cell contact, as in reproduction. This allows for inheritance of genetic information between distantly related lineages outside the vertical inheritance pathway implicit in cell division.

Hydrogenoclastic methanogenesis (Wood-Ljungdahl Pathway): A set of biochemical reactions used by some bacteria and archaea for energy production. The pathway uses hydrogen and carbon dioxide (CO_2) to produce methane and Acetyl-CoA, an important molecule for energy production. This is a biological source of methane production.

Hydrolysis: A reaction involving the breaking of a bond in a molecule using water. The reaction mainly occurs between an ion and water molecules and often changes the pH of a solution.

Hydrothermal: Relating to the action of heated water inside the crust of a planetary body.

Hyperthermophile: An organism with an optimum growth temperature of 80°C or higher.

Hypolith: A photosynthetic organism that lives underneath rocks for radiation and wind protection in climatically extreme deserts.

IDP: Interplanetary dust particle.

Lithoautotroph: A microbe which derives energy from reduced compounds of mineral origin. See **Chemolithoautotroph**.

MARSIS: Mars Advanced Radar for Subsurface and Ionosphere Sounding.

MEPAG: Mars Exploration Program Analysis Group.

Metabolism: The processes or chemical changes in a cell by which food is built up (anabolism) into living protoplasm and by which protoplasm is broken down (catabolism) into simpler compounds with the exchange of energy.

Metabolite: A substance that is formed in or necessary for **metabolism**. See **Metabolism**.

Methanogen: An organism capable of producing methane from the decomposition of organic material.

Microbe: A generic term for any prokaryotic or eukaryotic single-cell organism.

MSL: Mars Science Laboratory.

Oligotroph: A microorganism specifically adapted to grow under conditions of low nutrient supply.

Olivine: a magnesium iron silicate mineral $(FeMg)_2SiO_4$.

Oxidation/Reduction: The change in the oxidation state of atoms or ions due to the "loss" or "gain" of electrons.

Permafrost: A thick subsurface layer of soil that remains frozen throughout the year.

PHX: Phoenix Mars Lander.

Polar dark dune streaks: Dark markings along dune ridges, revealed during what is believed to be polar defrosting.

PP: Planetary Protection.

Psychrotolerant organism: An organism that has a maximum growth temperature of 35°C, an optimal growth temperature of 15°C or lower, and a minimum growth temperature of 0°C or lower.

Psycrophile: An organism that has a maximum growth temperature of 20°C, an optimal growth temperature of 15°C or lower, and a minimum growth temperature of 0°C or lower.

Recurring Slope Lineae (RSL): Narrow, dark markings on steep slopes in the equatorial regions of Mars that appear and incrementally lengthen during warm seasons and fade in cold seasons.

Redox couples: A coupled series of chemical reactions driven by the simultaneous loss of electrons from one species (oxidation) and the gain of electrons from a second species (reduction). See **Oxidation/Reduction**.

RSL: Recurring Slope Lineae. See **Recurring Slope Lineae**.

Saturated porosity: The open space of a rock (between grains or within cavities) being completely full of frozen water or carbon dioxide (CO_2) with respect to Mars.

Serpentinization reaction: A metamorphic process in which ultrabasic rocks react with water to create a variety of hydrous, magnesium-iron phyllosilicate minerals known collectively as serpentine. The process is endothermic and results in the liberation of hydrogen, methane, and hydrogen sulfide.

SHARAD: Shallow Subsurface Radar.

Slope streaks: Narrow, avalanche-like features common on dust-covered slopes around the equatorial regions of Mars.

Spore: A single-celled asexual reproductive unit created by a variety of microorganisms to aid in their dispersal and survival over extended periods of time in adverse environmental conditions.

SR: Special Region.

SR-SAG2: Special Regions Science Analysis Group 2.

Sterilization: A procedure that destroys all living microorganisms, including vegetative forms and spores. In practice, a completely sterile state is rarely achieved.

Sublimate: The change of a solid substance directly to vapor upon heating.

Tetrad: A group of four. In context, a group of four microbial cells.

TGO: Trace Gas Orbiter.

Thermophile: An organism that can survive and grow in high-temperature environments.

Translocation: Removal of things from one place to another; substitution of one thing for another.

Vapor pressure: The pressure exerted by a vapor in thermodynamic equilibrium with its solid or liquid phases at a given temperature in a closed system. The equilibrium **vapor pressure** is an indication of a liquid's evaporation rate.

Water activity (a_w): Effective or useable water content of a system. Water activity is defined as the ratio of the partial pressure of water vapor associated with a system to that of pure water at the same temperature. As such, water activity is related to relative humidity expressed as a fraction. Therefore, pure water has an a_w of 1. Whereas, an a_w of 0 indicates the absence of "free" water molecules.

Wood-Ljungdahl Pathway (hydrogenoclastic methanogenesis): A set of biochemical reactions used by some bacteria and archaea for energy production. The pathway uses hydrogen and carbon dioxide (CO_2) to produce methane and Acetyl-CoA, an important molecule for energy production. This is a biological source of methane production.

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Letter Requesting This Study

National Aeronautics and Space Administration
Headquarters
Washington, DC 20546-0001

OCT 03 2014

Reply to Attn of: Science Mission Directorate

Dr. David N. Spergel
Chair, Space Studies Board
National Research Council
500 Fifth Street, NW
Washington, DC 20001

Dear Dr. Spergel:

In accordance with international treaty obligations, NASA maintains a planetary protection policy to avoid biological contamination of other worlds, as well as to avoid the potential for harmful effects on the Earth due to the return of extraterrestrial materials by spaceflight missions. NASA Policy Directive 8020.7 requires that planetary protection requirements be based on recommendations from both internal and external advisory groups, but most notably the Space Studies Board (SSB). NASA relies on the Board's ability to synthesize input from a wide spectrum of the science community and provide expert advice and recommendations, both as an advisory body and as the U.S. representative to the International Council for Science's Committee on Space Research (COSPAR), which is consultative to the United Nations Committee on the Peaceful Uses of Outer Space. As such, the SSB's recommendations on planetary protection are internationally recognized as authoritative and independent of NASA.

Planetary protection requirements for each mission and target body depend upon the type of encounter it will have (e.g., flyby, orbiter, or lander) and the nature of its destination (e.g., a planet, moon, comet, or asteroid). If the target body has the potential to provide clues about the origins and evolution of life or prebiotic chemical evolution, a spacecraft going there must meet a higher level of cleanliness, and some operating restrictions will be imposed. Spacecraft going to target bodies with the potential to support Earth life must undergo stringent cleaning and bioload-reduction processes, and may be subject to greater operating restrictions.

Current COSPAR planetary protection policy designates the categorization IVc for spacecraft potentially accessing a so-called Special Region on Mars, and imposes specific constraints on spacecraft development and operations. A Special Region is defined as a location on or within Mars where Earth life might survive and proliferate. Previous planetary protection studies have revealed that Earth life can reasonably be expected to proliferate if the temperature is above -25 C and the water activity is greater than 0.5 (relative humidity of 50%), simultaneously.

At NASA's request, the community-based Mars Exploration Program Analysis Group (MEPAG) established the Special Regions Science Analysis Group (SR-SAG2) to examine the quantitative definition of Special Regions and propose modifications to it, as necessary, based upon the latest scientific results. SR-SAG2 was also asked to conduct a preliminary analysis of specific environments that should be considered "special" and "non-special."

As NASA develops its plans for the Mars 2020 mission and, in particular, finalizes the selection of candidate landing sites, it would be very helpful for the SSB to review the conclusions and recommendations contained in MEPAG's SR-SAG2 report and assess their consistency with current understanding of both the martian environment and the physical and chemical limits for the survival and propagation of microbial and other life on Earth.

As you know, the European Space Agency (ESA) also has ambitious plans for future Mars exploration missions. It is our understanding that ESA has requested the European Science Foundation (ESF) conduct a very similar review of MEPAG's SR-SAG2 report. Given the close working relationship between NASA and ESA, in general, and their respective Planetary Protection Offices, in particular, the NRC should engage with ESF and explore the possibility of a joint study responsive to the needs of both agencies. It is expected that a detailed scope and objectives Terms of Reference for such a joint undertaking will be established by consultation between the NRC and the ESF.

I would like to request that the NRC submit a plan for establishment of an ad hoc committee to review the current planetary protection requirements for Mars Special Regions and their proposed revision as outlined in the 2014 Special Regions report of the Mars Exploration Program Analysis Group (MEPAG SR-SAG2). The resulting report from the review should include recommendations for an update of the planetary protection requirements for Mars Special Regions. The results of the assessment will be most useful to NASA if it is received no later than the summer of 2015. The task performance period itself should extend to November 30, 2015, to cover printing and distribution of the final report.

Once agreement on the scope, cost, and schedule for the proposed study has been achieved, the Contracting Officer will issue a task order for implementation. Dr. Catharine A. Conley, Planetary Protection Officer, will be the technical point of contact for this effort and may be reached at cassie.conley@nasa.gov or (202) 358-3912.

Sincerely,

John M. Grunsfeld
Associate Administrator for
Science Mission Directorate

cc: Science Mission Directorate/Dr. M. Allen
- Dr. C. Conley
- Ms. D. Holland
- Dr. B. Pugel

E

Committee and Staff Biographical Information

PETRA RETTBERG, *Chair*, is team leader of the astrobiology-group at the German Aerospace Center (DLR) Institute of Aerospace Medicine. At DLR, she has served as the deputy head of the Radiation Biology Department, head of the Astrobiology Research Group, and head of the Radiation Biology Research Group. Her research interests include astrobiology, planetary protection, microbiology, and photobiology. She was a member of the COSPAR Panel on Exploration and the COSPAR Panel on Planetary Protection (PPP). She is also a member of the European Space Sciences Committee (ESSC) of the European Science Foundation (ESF) Solar System and Exploration Panel (SSEP) and the European Space Agency (ESA) Planetary Protection Working Group (PPWG). She earned her Ph.D. in molecular biology from Ruhr-Universität Bochum in Germany.

ALEXANDRE ANESIO is professor of biogeochemistry in the School of Geographical Sciences at the University of Bristol in the United Kingdom. His research interests combine concepts from geography, biology, and chemistry to understand the carbon cycle in the cryosphere. He is also interested in a range of climate and human impacts on freshwaters such as ultraviolet radiation and mining, respectively. He earned his Ph.D. from Lund University in Sweden.

VICTOR BAKER is a Regents' Professor of the University of Arizona in the departments of hydrology and water resources, planetary sciences and geosciences. He has more than 35 years' experience in planetary science research, particularly in geological studies of Mars and Venus. He also has had long experience with interpretive studies of terrestrial remote sensing, especially in regard to his specialties in fluvial geomorphology and flood hydrology. Dr. Baker is a fellow of the American Geophysical Union, honorary fellow of the European Geosciences Union, fellow of the American Association for the Advancement of Science, and foreign member of the Polish Academy of Sciences. He was the 1998 president of the Geological Society of America, and he holds the 2001 Distinguished Scientist and 2010 Distinguished Career Awards from the Quaternary Geology and Geomorphology Division of that society. He is the author or editor of 18 scholarly books or monographs, 400 scientific papers and chapters, and more than 480 published abstracts and short reports. He received his Ph.D. in planetary sciences from University of Colorado. He has served on previous National Research Council (NRC) committees, including the Planning Committee for Global Change and Extreme Hydrologic Events: Testing Conventional Wisdom—A Workshop, the Committee on Hydrologic Science, and the Planning Committee on Research Applications Needs in Flood Hydrology Science: A Workshop.

JOHN A. BAROSS is professor of biological oceanography and the Astrobiology Program at the University of Washington, Seattle. He is an expert on microorganisms and viruses from volcanic environments, the limits of life, the origin and evolution of life; and life on other planets and moons. He received his Ph.D. in marine microbiology from the University of Washington. He also served on the ESF-ESSC Study Group on Mars Sample Return (MSR) Planetary Protection Requirements entitled "Mars Sample Return Backward Contamination Strategic Advice and Requirements." His NRC service includes chairing the Committee on the Limits of Organic Life in Planetary Systems, co-chairing the Committee for a Review of Programs to Determine the Extent of Life in the Universe, and co-chairing the Committee on the Origins and Evolution of Life, membership on the Steering Group for the Workshop on Size Limits of Very Small Microorganisms, Task Groups on Sample Return from Small Solar System Bodies, and Assessment of Planetary Protection Requirements for Spacecraft Missions to Icy Solar System Bodies, and Ad Hoc Task Group on Planetary Protection.

SHERRY L. CADY is chief scientist of biogeochemical imaging at the Environmental Molecular Sciences Laboratory at the Pacific Northwest National Laboratory in Richland, Washington, and professor emeritus in the Department of Geology at Portland State University in Portland, Oregon. Dr. Cady is an expert on how extremophile microbial communities interact with their environment and how microbial signatures are sequestered in the geological record. Her research focuses on using the molecular-to-macroscale chemical and morphological evidence of microbes preserved in geological materials (soils, sediments, and mineral precipitates) to detect signs of ancient life and predict how microbial communities throughout time have lived and responded to changes in their environment. Such research informs paleobiology and astrobiology search strategies. Dr. Cady is a Fullbright senior research scholar at the Universitié Cadi Ayyad, Faculty de Sciences, Marrakesh, Morocco. She earned her Ph.D. in geology from the University of California, Berkeley. She served as an NRC research associate at NASA Ames Research Center. Dr. Cady served on the NRC Committee to Review of the Next Decadal Mars Architecture and the Committee to Review Planetary Protection Requirements for Mars Sample-Return Missions.

CHRISTINE M. FOREMAN is an associate professor in the Department of Chemical and Biological Engineering at Montana State University. Her research revolves around the organization of microbial communities in relation to their physical environment, and the processing of nutrients and dissolved organic matter (DOM). She is interested in the contribution of DOM to global carbon budgets, including potential storage in ice, and how this DOM is responsive to enhanced ultraviolet radiation. Dr. Foreman has spent 11 seasons in Antarctica and 1 in Greenland investigating microbial interactions in the permanently ice covered lakes, streams, and glacial cryoconites, as well as studying deep ice from Lake Vostok and the WAIS Divide. In addition, these studies set the stage for future investigations of life on other icy planets and moons. Dr. Foreman is a member of the U.S. Ice Core Working Group, the U.S. Committee for Limnology and Geochemistry of the International Subcommittee on Antarctic Lake Environments, and past member of the U.S. Ice Drilling Program Office Subglacial Access Working Group. She has served on two NASA advisory panels for the Astrobiology Science and Technology for Exploring Planets program and the NRC Committee on NASA's Suborbital Research Capabilities.

ERNST HAUBER is a planetary scientist at the German Aerospace Center Institute of Planetary Research. His research interests focus on planetary geology. He has conducted work in the fields of geophysics, astrophysics and space science, and geomorphology. He is a co-investigator for several deep space instrument teams, and is currently serving as a member in ESA's Planetary Protection Working Group and the joint ESA/Roscosmos ExoMars Landing Site Selection Working Group. He earned his diploma for geology from Ludwig-Maximilians-Universität München.

GIAN GABRIELE ORI is professor of geology (faculty of science, Universita d'Annunzio, Italy) and director of the International Research School of Planetary Sciences in Pescara, Italy. Dr. Ori is an interdisciplinary scientist for geology of the Mars express mission, co-investigator of the high-resolution stereo camera, and co-investigator of radars aboard MRO and Cassini. He is in charge of the analysis of the landing sites for the ESA missions ExoMars 2016 and 2018. Dr. Ori has served on several advisory committees of ESA and he is currently member of executive committee of the NASA's Mars Exploration Program Analysis Group (MEPAG). He received his Ph.D.

for geological sciences from the Universita' di Bologna, (Italy). He served on the NRC's Committee on Preventing the Forward Contamination of Mars.

DAVID PEARCE is a professor of environmental microbiology in the Department of Applied Sciences at Northumbria University in the United Kingdom. At Northumbria, his underlying research theme is the use of microbiology to understand Polar ecosystem function and the potential for shifts in biogeochemical activity that may result from environmental change. He has worked with the British Antarctic Survey as a microbiologist, head of the Genomic Analysis Section of the Biological Sciences Division, and an aquatic microbial ecologist. His research interests include microbial biodiversity, environmental microbiology, microbial ecology, molecular ecology, microbial physiology, environmental genomics, extremophiles, life in extreme environments, exploring and applying new technology, and the potential of unknown ecosystems. He is a member of the British Ecological Society and the International Society for Microbial Ecology. He earned his Ph.D. in microbiology from King's College, University of London.

NILTON RENNO is a professor in the Department of Atmospheric, Oceanic, and Space Sciences at the University of Michigan. He was a visiting scholar at the University of Oxford Department of Physics in the United Kingdom and an associate professor (with tenure) at the University of Arizona Department of Planetary Sciences. His research is focused on instrument development and thermodynamics, astrobiology, and climate. As a member of the Mars Science Laboratory Team he was a recipient of the Space Foundation John L. "Jack" Swigert Jr. Award for Space Exploration and the American Institute of Aeronautics and Astronautics (AIAA) Foundation's Award for Excellence. He has been a member of the American Astronomical Society and the International Society for Optics and Photonics. He earned his Ph.D. in atmospheric sciences from the Massachusetts Institute of Technology (MIT). He served on the NRC's Panel on Earth and Atmospheric Sciences.

GARY RUVKUN is professor of genetics at Harvard Medical School. His laboratory investigates neuroendocrine control of *C. elegans* development, metabolism, and longevity, as well as control of temporal pattern formation by heterochronic genes. He also has begun new studies on the genetic control of molting and neurotransmitter tranport. His laboratory has also started work with the Church Laboratory and engineers at MJ Research and the MIT Center for Space Research to develop a miniature thermal cycler and protocols to send to Mars in search of microbial life. As a postdoc he worked with Bob Horvitz at MIT and Walter Gilbert at Harvard, where he explored the heterochronic genes that control the temporal dimension of development. This work led to the discovery of the first microRNA genes and their mRNA targets by the Ambros and Ruvkun laboratories, the discoveries by the Ruvkun Laboratory that the mechanism of microRNA regulation of target mRNAs is post-transcriptional and that some microRNA genes are conserved across animal phylogeny. Dr. Ruvkun is a graduate of UC Berkeley (A.B. biophysics) and Harvard University (Ph.D. biophysics). He is a member of the NAS and the IOM. He has served on the NRC's KFoS Five-Year Review Committee, the Organizing Committee for the Eleventh Annual Symposium on Frontiers of Science, and the Committee on Astrobiology and Planetary Science.

BIRGIT SATTLER is an associate professor at the University of Innsbruck, Austria, at the Institute of Ecology. Her research interests include bacterial secondary production and activity, primary production, microbial communities in ice layers of alpine and Antarctic lakes, microbial processes in snow and atmosphere, and ice physics. Dr. Sattler earned her Ph.D. in microbiology and limnology at the University of Innsbruck and specializes in the microbial ecology of cold environments such as ice, snow, and the atmosphere.

MARK P. SAUNDERS is an independent consultant. Since retiring from NASA in December 2008, he has been consulting to various NASA offices providing program/project management and systems engineering expertise. This has included support to the Office of Chief Engineer, the Office of Independent Program and Cost Evaluation, the Mars Program, and the Science Office for Mission Assessments (at Langley Research Center [LaRC]). He has participated in the rewriting of NASA's policy on program/project management; advised and supported the agency's independent program/project review process; and has supported the review of various programs and projects. At NASA Headquarters he served as director of the independent program assessment office, where he was responsible for enabling the independent review of the agency's programs and projects at life cycle milestones to ensure the highest probability of mission success. At LaRC, he was initially the deputy director and then the director of the Space Access and Exploration Program Office and had the responsibility for planning, directing, and coordinating the center's research, technology, and flight programs for advanced aerospace transportation and human/robotic exploration systems. Prior to this, he was the manager of exploration programs and led all LaRC space exploration research and development activities supporting the agency's Aerospace Technology, Human Exploration, and Development of Space and Space Science Enterprises. At the Office of Space Science, he served as program manager for the Discovery Program, and at the Space Station Freedom program operations, he served as special assistant to the deputy director. He received the Presidential Meritorious Rank Award in 2008, Outstanding Performance awards: 1982, 1994-2008, and the NASA Outstanding Leadership Medals in 1998, 2004, 2006. He earned his B.A. at the Georgia Institute of Technology in industrial engineering. He has served on the NRC's Committee on Astrobiology and Planetary Sciences.

DIRK WAGNER is the geomicrobiology section head in the chemistry and material cycles department at the GFZ German Research Center for Geosciences Helmholtz Centre Potsdam in Potsdam, Germany. He is also professor of geomicrobiology and geobiology at the Institute of Earth and Environmental Sciences at the University of Potsdam. He was the leader of the working group Geomicrobiology in Periglacial Regions at the Helmholtz Centre for Polar and Marine Research. His research interests include enrichment, isolation, and characterization of extremophilic microorganisms; quantification of element fluxes and the fundamental microbial processes in terrestrial ecosystems; the molecular ecological characterization of microbial communities in extreme environments; reaction and adaptation of microorganisms to changing environmental conditions; and astrobiology. He has served as an editorial board member of the *Microbiology Ecology* and *Permafrost and Periglacial Processes* journals of the Federation of European Microbiological Societies. Dr. Wagner earned his Ph.D. in soil microbiology at the Institute of Soil Science at the University of Hamburg.

FRANCES WESTALL is the director of research (exobiology) at the Centre National de la Recherche Scientifique (CNRS). She has conducted research in the subject of geobiology, specifically fossil bacteria, at the University of Nantes in France and the University of Bologna in Italy. She was a visiting post-doctoral scientist at the Lunar and Planetary Institute, where her work focused on bacterial palaeontology, prebiotic molecules, and early archean geology. She was an NRC fellow at NASA Johnson Space Center where she conducted research in subjects of bacterial palaeontology and bacteriomorphs in martian meteorites. Her research interests include martian geology and potential palaeontology and early Earth geological history. Dr. Westall has co-authored publications that have been awarded the 2001 Gerald A. Soffen Memorial Award and the 2014 WITec Paper Award. She is president of the European Astrobiology Network Association. She earned her Ph.D. in marine geology from the University of Cape Town, South Africa.

Staff

EMMANOUIL DETSIS is a science officer with the ESF's Science Support Office. His main role at ESF consists of project management, coordination, and support for the framework program activities, and ESA-commissioned studies. His interests include technology foresight and low-level technology maturation concepts, innovative concepts for space exploration, life support systems, space nuclear power, computational and theoretical astrophysics, and planetary protection policy aspects. He earned his Ph.D. in astrophysics from the University of Edinburgh and a master's in space science from the International Space University.

DAVID H. SMITH joined the Space Studies Board (SSB) in 1991. He is the senior staff officer and study director for a variety of NRC activities in astrobiology, planetary science, and planetary protection. He also organizes the SSB's summer intern program and supervises most, if not all, of the interns. He received a B.Sc. in mathematical physics from the University of Liverpool in 1976, achieved the honors standard in Part III of the Mathematics Tripos at the University of Cambridge in 1977, and a D.Phil. in theoretical astrophysics from Sussex University in 1981. Following a postdoctoral fellowship at Queen Mary College University of London (1980-1982), he held the position of associate editor and, later, technical editor of *Sky and Telescope*. Immediately prior to joining the staff of the SSB, Dr. Smith was a Knight Science Journalism Fellow at MIT.

MICHAEL MOLONEY is the director for Space and Aeronautics at the SSB and the Aeronautics and Space Engineering Board of the National Academies of Sciences, Engineering, and Medicine. Since joining the ASEB/SSB, Dr. Moloney has overseen the production of more than 40 reports, including four decadal surveys—in astronomy and astrophysics, planetary science, life and microgravity science, and solar and space physics—a review of the goals and direction of the U.S. human exploration program, a prioritization of NASA space technology roadmaps, as well as reports on issues such as NASA's Strategic Direction, orbital debris, the future of NASA's astronaut corps, and NASA's flight research program. Before joining the SSB and ASEB in 2010, Dr. Moloney was associate director of the Board on Physics and Astronomy (BPA) and study director for the decadal survey for astronomy and astrophysics (Astro2010). Since joining the NRC in 2001, Dr. Moloney has served as a study director at the National Materials Advisory Board, the BPA, the Board on Manufacturing and Engineering Design, and the Center for Economic, Governance, and International Studies. Dr. Moloney has served as study director or senior staff for a series of reports on subject matters as varied as quantum physics, nanotechnology, cosmology, the operation of the nation's helium reserve, new anti-counterfeiting technologies for currency, corrosion science, and nuclear fusion. In addition to his professional experience at the National Academies, Dr. Moloney has more than 7 years' experience as a foreign-service officer for the Irish government—including serving at the Irish Embassy in Washington and the Irish Mission to the United Nations in New York. A physicist, Dr. Moloney did his Ph.D. work at Trinity College Dublin in Ireland. He received his undergraduate degree in experimental physics at University College Dublin, where he was awarded the Nevin Medal for Physics.

NICOLAS WALTER is currently a senior science officer at the ESF. He has been involved in project and study management for the ESA and the European Commission FP7 and Horizon 2020 projects (as coordinator or project manager). He has coordinated and initiated numerous projects in the fields of astrobiology, life in extreme environments, Mars analogues studies, planetary protection, and life sciences in space. He is responsible for peer-review activities at the ESF and was heavily involved in evaluation studies of ESA programmes. He earned his master's in space science from the International Space University.

JEAN-CLAUDE WORMS is currently the head of the Science Support Office of the ESF. As of January 1, 2016, he will assume the new role as ESF's chief operating officer. He holds a Ph.D. in physics (astronomy and space science) from the University Pierre et Marie Curie (Paris 6), has over 15 years of research experience in international space research projects, and more than 20-years' experience in research management and strategic planning, assessing programmatic aspects of space agencies and research councils, coordinating policy and strategy at national and international level, and dealing with officials, executives, and scientific interest groups worldwide. He is involved in ESA and European Commission high-level science advisory structures and has participated with an observer status to ESA's Ministerial Conferences since 1999.

ANDREA REBHOLZ joined the SSB as a program associate in 2009. She began her career at the National Academies in 2005 as a senior program assistant for the Institute of Medicine's Forum on Drug Discovery, Development, and Translation. Prior to the Academies, she worked in the communications department of a DC-based think tank. Ms. Rebholz graduated from George Mason University's New Century College in 2003 with a bachelor of arts in integrative studies—event management and has more than 10 years of experience in event planning, project administration, and editing.

DANIELLE YOUNGSMITH is a Lloyd V. Berkner space policy intern at the SSB and a self-designed astrobiology major and physics minor at Barnard College of Columbia University in New York City. She spent the majority of a year away from Columbia conducting exobiology, astrophysics, and human factors research at NASA Ames Research Center and through the SETI Institute. She was able to bring this biology research on habitability to the Mars Desert Research Station while conducting a simulated human mission to Mars.